

Development and Evaluation of Improved
Fine Particulate Filter Systems

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DEVELOPMENT AND EVALUATION
OF IMPROVED FINE PARTICULATE
FILTER SYSTEMS

by

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16. ABSTRACT The report describes efforts to relate coal and fly ash properties to the fabric filter specific resistance coefficient, $K_{sub 2}$, and to extend the GCA/EPA fabric filter model to include pulse-jet filter theory. Fly ashes from coal produced in various parts of the U.S., including low sulfur western coals, were examined for physical and chemical properties that might correlate with the magnitude of the $K_{sub 2}$ parameter. Variation in $K_{sub 2}$ between fly ashes has been noted, but its specific causes have not been delineated. Results of this work showed a strong correlation between fly ash size, coal ash content, and $K_{sub 2}$. Electrical charge and method of coal firing exhibited weak correlations. However, coal sulfur content, fusion properties, and chemical structures showed no clear-cut correlations. The relevant literature on pulse-jet filter theory was assessed to develop guidelines for developing a predictive model. The effects of jet size, air volume, and pulse intensity were related to pressure loss. Energy transfer from the jet pulse to the fabric was explored. Finally, predictive equations were developed for estimating total pressure loss over a range of collector design and operating parameters.		
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ABSTRACT

The filterability of fly ashes emitted by coal burning power stations is described, including that of several ashes generated by low sulfur western coal combustion that are best controlled by fabric filtration. Chemical and mineralogical analyses of the coals were examined to determine possible relationships between coal and ash properties and filtration behavior. Both fly ash size and coal ash content correlated strongly with the fly ash specific resistance coefficient, K_2 . Weaker, but discernible, correlations were shown for electrical charge behavior and method of coal firing. Coal sulfur content, ash fusion properties, and chemical structures originally expected to influence particle size showed no clear-cut effects on filtration characteristics. The relevant literature on pulse jet filter theory and applications was assessed to develop coherent guidelines for designing predictive filter models. The effects of jet size and location, jet air volume, and the intensity and duration of the jet pulses were related to pressure loss. Energy transfer from the jet pulse to the fabric was explored in terms of jet pressure, solenoid valve action, the ratio of pulse volume to bag volume, and the kinetic properties of the felt bags. Finally, predictive equations were developed for estimating pressure loss over a broad range of collector design and operating parameters.

CONTENTS (continued)

7. Extension of Existing Mathematical Model Computer Program to	
Include Pulse Jet Cleaning	83
Project Objectives	83
Background	83
Common Misunderstandings of Pulse Jet Collector	
Operation	84
Unique Features of Pulse Jet Operation	92
Proposed Modeling Approach	106
References	118
Appendices	
A. Proposed Technique for Field Determination of the Specific	
Resistance Coefficient, K_2	122
B. Fly Ash Size Parameters	125
C. Drag vs. Fabric Loading Curves for Test Fly Ashes	140

FIGURES

<u>Number</u>		<u>Page</u>
1	Major U.S. coal producing regions and distribution of coal-burning utilities and industries using fabric filters	15
2	Estimated coal analyses, regional basis	19
3	Effect of grindability and fineness on pulverizer capacity . .	22
4	Fly ash mass distribution versus method of coal firing	25
5	Acidic content of ash versus ash fusion temperature	34
6	Idealized phase diagram showing physical state and temperature of ash as a function of base content.	34
7	Characterizing ratios versus location of coal seam	36
8	Fluid temperature versus dolomite percentages for various eastern and western coal ashes computed from data appearing in Table 5.	38
9	Total iron oxide in coal versus iron pyrite equivalent of iron oxide	41
10	Effect of sulfur content of "as received coals" on ash softening point	42
11	Effect of total ash content on ash softening point	43
12	NBS-type dust generator	55
13	GCA bench-scale fabric filter test assembly	57
14	Typical drag versus fabric loading curve used to estimate specific resistance coefficient, K_2	58
15	Schematic, drag versus loading curves for same dust using membrane filters and woven fabrics	60
16	Schematic, simplified pulse cleaning system	63

FIGURES (continued)

<u>Number</u>		<u>Page</u>
17	Particle size distribution for Southwestern Public Service resuspended fly ash, Andersen Mark III impactor measurements. Sample 1	67
18	Drag versus fabric loading, Southwestern Public Service's fly ash, A/C = 0.61 m/min	71
19	Specific resistance coefficient (K_2) versus specific surface parameter (S_g^2) with 95 percent confidence interval indicated by dotted lines. (P) and (S) refer to pulverized and stoker firing. Circles delineate charge effects.	73
20	Dust cake specific resistance coefficient (K_2) versus percent ash in coal	76
21	Fly ash fraction removed versus separation or adhesive force	79
22	Pressure gradient versus location and time after pulse initiation for 1.22 m long (4 ft) Dacron felt bag	86
23	Pressure variations along 1.22 m long (4 ft) bag versus solenoid valve open time.	87
24	Concurrent pressure/time traces, 1.83 m (nominal 6 ft) long Dacron felt bag for a 621 kPa (90 psig) pulse and 0.1 s duration.	88
25	Differential pressure versus time for Dacron bags 1.22 m x 11.4 cm (4 ft x 4.5 in.), fly ash filtration, 1 pulse per minute at 483 kPa (70 psig)	89
26	Bag profiles versus time after pulse initiation for a 1.22 m (4 ft) long bag. Bubble concept (a) vs. theory (b) (c) (d)	90
27	Resistance characteristics for fly ash and Dacron felt at $C_i = 27.6 \text{ g/m}^3$ and $V = 2.6 \text{ m/min}$	93
28	Static displacement of fabric surface at fixed differential pressures with used bags, 1.22 m long x 11.4 cm diameter	97
29	Characteristic pressures before and after steady-state filtration is achieved	99
30	Talc filtration velocity versus inlet concentration at constant pressure loss	103

FIGURES (continued)

<u>Number</u>		<u>Page</u>
31	Fractional dust removal versus pulse jet pressure at constant W	104
32	Pressure loss and K_2 values for fly ash with Dacron felt, inlet concentration = 27.6 g/m ³ , filtration velocity = 2.6 m/min. Linear intercept at time zero is effective residual pressure loss, $(P_E)\Delta W$	108
33	Effective residual pressure loss versus $d(\Delta p)/dt$, 0 to 0.01 s. Fly ash filtration at 2.6 m/min	112
A-1	Test apparatus for K_2 determination schematic with 47-mm membrane filter circles	124
B-1	Particle size distribution for Southwestern Public Service resuspended fly ash, Andersen Mark III impactor measurements. Sample 1	126
B-2	Particle size distribution for Crisp County Power Commission resuspended fly ash, Andersen Mark III impactor measurements. Sample 2	127
B-3	Particle size distribution for Kramer Station resuspended fly ash, Andersen Mark III impactor measurements. Sample 4	128
B-4	Particle size distribution for Texas Utilities resuspended fly ash, Andersen Mark III impactor measurements. Sample 6	129
B-5	Particle size distribution for U.S. Steel, Provo, Utah resuspended fly ash; Andersen Mark III impactor measurements. Sample 7	130
B-6	Particle size distribution for Amalgamated Sugar Sample A resuspended fly ash, Andersen Mark III impactor measurements. Sample 8A.	131
B-7	Particle size distribution for Amalgamated Sugar--Sample B resuspended fly ash, Andersen Mark III impactor measurements. Sample 8B.	132
B-8	Particle size distribution for Pennsylvania Power & Light, Holtwood Station resuspended fly ash, Andersen Mark III impactor measurements. Sample 9.	133
B-9	Particle size distribution for DuPont's Waynesboro plant resuspended fly ash, Andersen Mark III impactor measurements. Sample 12	134

FIGURES (continued)

<u>Number</u>		<u>Page</u>
B-10	Particle size distribution for Westinghouse Hanford, resuspended fly ash, Andersen Mark III impactor measurements. Sample 13	135
B-11	Particle size distribution for the Case Medical Center resuspended fly ash, Andersen Mark III impactor measurements. Sample 14.	136
B-12	Particle size distribution for Republic Steel resuspended fly ash, Andersen Mark III impactor measurements. Sample 16. . .	137
B-13	Particle size distribution for Colorado-Ute Electric Association Nucla Station--Hopper Sample resuspended fly ash, Andersen Mark III impactor measurements. Sample 17A.	138
B-14	Particle size distribution for Colorado-Ute Electric Association Nucla Station - Shake Down Sample resuspended fly ash, Andersen Mark III impactor measurements. Sample 17B	139
C-1	Drag versus fabric loading, Southwestern Public Service. A/C = 0.61 m/min.	141
C-2	Drag versus fabric loading, Crisp County. A/C = 0.61 m/min . .	142
C-3	Drag versus fabric loading, Kramer Station. A/C = 0.61 m/min .	143
C-4	Drag versus fabric loading, Texas Utilities. A/C = 0.61 m/min.	144
C-5	Drag versus fabric loading, U.S. Steel. A/C = 0.61 m/min . . .	145
C-6	Drag versus fabric loading, Amalgamated Sugar "A". A/C = 0.61 m/min.	146
C-7	Drag versus fabric loading, Amalgamated Sugar "B". A/C = 0.61 m/min.	147
C-8	Drag versus fabric loading, PPL, Holtwood. A/C = 0.61 m/min. .	148
C-9	Drag versus fabric loading, DuPont, Waynesboro. A/C = 0.61 m/min.	149
C-10	Drag versus fabric loading, Westinghouse, Hanford. A/C = 0.61 m/min.	150
C-11	Drag versus fabric loading, Case Medical Center. A/C = 0.61 m/min.	151

FIGURES (continued)

<u>Number</u>		<u>Page</u>
C-12	Drag versus fabric loading, Republic Steel. $A/C = 0.61$ m/min .	152
C-13	Drag versus fabric loading, Colorado Ute, Nucla Station (Hopper Sample). $A/C = 0.61$ m/min.	153
C-14	Drag versus fabric loading, Colorado Ute, Nucla Station (Bag Shakedown). $A/C = 0.61$ m/min	154

TABLES

<u>Number</u>		<u>Page</u>
1	Estimated Coal Production Used by Utilities and Industry for Electrical Power, Steam, or Heating Purposes	11
2	Distribution and Properties of Typical U.S. Coals (Lignite to Bituminous) with Estimated Fractions Used for Power Generation Purposes	16
3	Common Mineral Constituents of Coal Seam Floors, Partings, and Overburdens: Chemical Composition and Physical Properties	21
4	Reported Mass Median Diameters (μm) for Particulate Emissions from Various Coal-Fired Furnaces	24
5	Chemical Constituents and Fusion Properties of U.S. Coals . . .	26
6	Coal Fouling and Slagging Parameters That May Affect Fly Ash Filterability	30
7	Softening Temperatures, Ash Constituents, and Characterizing Ratios for Several U.S. Coals	31
8	Chemical Composition of Typical Coal Ashes	32
9	Sulfur-Iron Balance for Typical U.S. Coals	40
10	Tentative Specifications for Fly Ash Sampling Based on Coal Source, Properties, and Firing Method	47
11	Coal Fly Ash Samples Received or Suppliable for Laboratory Testing	48
12	Fly Ash Suppliers and Coal Rank, Source, and Combustion System	50
13	Ash and Coal Properties	51
14	Mineral Constituents of Coal Ashes	52

TABLES (continued)

<u>Number</u>		<u>Page</u>
15	Classification of Fly Ash Samples by Selection Criteria	54
16	Measured and Computed Values for Various Fly Ash Parameters . .	69
17	Correlation Coefficients for K_2 with Various Coal and Fly Ash Properties	70
18	Fractional Surface Cleaning of Used Dacron Felt Versus Pulse Pressure--Laboratory Panel Tests	81
19	Predicted Cleaning Parameters, a_c , for Various Coal Fly Ashes	82
20	Fabric and Pressure Parameters for Estimating Maximum Deceleration of a Lightweight, Moderately Stiff Dacron Felt	97
21	Effect of Pulse Pressure, Inlet Concentration, and Filtration Velocity on Steady-State (W_c) Fabric Loading	102
22	Fractional Surface Cleaning of Used Dacron Felt Versus Pulse Pressure--Laboratory Panel Tests	105
23	Experimentally Determined Descriptors of Pulsed Bag Motion Dacron (Needled) Felt Bag, 1.22 m long, 11.4 cm diameter . .	109
24	Delivered Air Volume (Primary Air) Versus Reservoir Pressure, Direct Pulses	113
25	Variation of Maximum Cleanside Bag Pressure and $d(\Delta p)/dt$ with Reservoir Pressure. Fly Ash Filtration at 2.7 m/min, 1.22 m x 11.4 cm Bag	115

NOMENCLATURE

<u>Symbol</u>	<u>Description</u>	<u>Unit(s)</u>
A	Bag area, system	m ²
A _j	Jet nozzle cross section	m ²
a _i	Bag area, ith surface area increment	m ²
a _{max}	Peak bag deceleration	m/s ²
a	Fabric and dust acceleration	m/s ²
C	Inlet dust concentration	g/m ³
C _d	Coefficient of discharge	dimensionless
F _A	Adhesive force/unit area	N/m ²
F _s	Separating force/unit area	N/m ²
G	Bag flexing parameter	cm ² ·s ² /g
g	Dust mass (grams)	g
g _a	Gravity acceleration	cm/s ² (or "g's")
gr	Dust mass (grains)	gr
K ₂	Specific resistance coefficient	N·min·g m
(K ₂) _c	Specific resistance coefficient cycled dust loading	N·min·g m
k	Constant in Eq 26	2.12
M	Jet air, mass flow rate	g/s
M _e	Bag elongation parameter	cm ² ·s ² /g
MMD	Mass median diameter, actual	μm
N	Particle contacts per unit area	cm ⁻²
n _b	Number of bags	
P	Filter pressure loss	kPa
P _b	Bag static pressure before pulsing	kPa
(P _E) _w	Filter pressure loss (effective) before filtration	kPa
P _j	Pulse jet reservoir pressure, gauge	kPa
P _{ja}	Pulse jet reservoir pressure, absolute	kPa
P _{max}	Maximum pressure clean side of bag, gauge	kPa
r	Bag radial displacement	cm
r _{max}	Maximum bag displacement	cm
S	Filter drag	N·min/m ³
S _E	Filter drag, effective residual	N·min/m ³
S _i	Filter drag, ith surface area increment	N·min/m ³
S _R	Residual fabric drag	N·min/m ³
S	Filter drag, system average	N·min/m ³
T _{ja}	Absolute temperature, compressed air	°K
t _s	Solenoid valve opening time	s
t	Time, filtration interval	min

NOMENCLATURE (continued)

<u>Symbol</u>		<u>Unit(s)</u>
V	Filtration (face) velocity	m/min
V _b	Bag volume	m ³
V _{max}	Maximum radial velocity	cm/s
V _p	Primary jet air volume	m ³
V _{ps}	Combined primary (V _p) and secondary (V _s) jet air volumes	m ³
V _s	Secondary jet air volume	m ³
W _R	Residual fabric dust loading	g/m ²
W	Fabric dust loading (Areal density)	g/m ²
W _c	Fabric dust loading, cycling	g/m ²
W	Dust loading added during filtration interval	g/m ²
α	Constant in Equation 16	Dimensionless
β	Constant in Equation 16	Dimensionless
ρ	Bag and dust mass per unit area	g/m ²
ρ _b	Ambient (bag) air density	kg/m ³
σ _g	Geometric standard deviation	Dimensionless
σ _{max}	Bag stopping force per unit area	g/cm·s ²

CONTENTS

Abstract	iii
Figures	vii
Tables	xii
Nomenclature	xiv
Acknowledgements	xvi
1. Executive Summary	1
Program Objectives	1
Results	1
Conclusions.	2
2. Introduction	5
Program Objectives	5
Methodology	6
3. Technical Background	7
Coal Properties versus Fly Ash Specific Resistance	
Coefficient, K_2	7
Coal and Fabric Properties versus Fly Ash Cleaning	
Parameter, a_c	8
Coal Sources, Production Statistics, Utilization, and	
Properties	10
Potential Impact of Coal Chemistry on Fly Ash Behavior	29
4. Basis for Selection of Representative Coals	45
5. Test Materials, Equipment, and Procedures	49
Test Fly Ashes	49
Fly Ash Aerosolization	53
Filter Test Assembly	56
Fabric Cleanability Tests	59
Particle Size Measurements	62
6. Results	65
Introduction	65
Fly Ash Size Properties	66
Specific Resistance Coefficient, K_2	68
Effect of Boiler Type and Firing Method on K_2	72
Effect of Electrical Charge on K_2	74
Effect of Coal Sulfur Content on K_2	74
Effect of Coal Ash Content on K_2	75
Base-to-Acid Ratio	75
Effect of Filtration Velocity on K_2	77
Fly Ash Cleaning Characteristics	77
Test Results	80

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SECTION 1

EXECUTIVE SUMMARY

PROGRAM OBJECTIVES

Coal and Fly Ash Properties versus Fly Ash Filterability

The primary objective of the research described in this paper was to investigate possible relationships between coal and ash properties and fly ash filtration characteristics. It was postulated that certain chemical and physical properties of coals might have some predictive value in determining the specific resistance coefficients, K_2 , of their resultant fly ashes. Since this parameter is an important index of fabric filter performance, a reliable estimation method would prove valuable in the design and analysis of reverse-air and/or mechanical-shake cleaned fabric filter systems.

Mathematical Model for Pulse Jet Filtration

A second program objective was to extend the capabilities of the existing EPA/GCA filtration model to include pulse jet devices or, alternatively, to develop a new model if the former system could not be practically modified. The bases for developing a modeling protocol were the correlations observed among several past and present GCA studies as well as the results of other researchers.

RESULTS

Coal and Fly Ash Properties versus Fly Ash Filterability

The results of a survey of U.S. coal sources, types, compositions, production, and uses are described with the emphasis on coals whose particulate combustion effluents are controllable with fabric filters. The filterability of fly ashes emitted by coal burning power stations is described, including that of several ashes generated by low sulfur western coal combustion and best controlled by fabric filtration. Physical and chemical properties of the coals per se as well as their mineral constituents were evaluated for potential impact on resultant fly ashes. Several characterizing criteria commonly used to delineate coal fouling and slagging properties were examined for probable impact upon fly ash size and surface properties. Consideration was also given to the method of coal combustion, operating temperatures, fusion and hardness properties of mineral constituents, and slag viscosity as possible factors in determining fly ash filtration characteristics. High alkalinity contents were examined for their

potential to increase fly ash, acid gas, and moisture sorption. Both fly ash size and coal ash content correlated strongly with the fly ash specific resistance coefficient, K_2 . Weaker, but discernible, correlations were shown for electrical charge behavior and method of coal firing. Coal sulfur content, ash fusion properties, and chemical structures originally expected to influence particle size showed no clear-cut effects on filtration characteristics.

Mathematical Model for Pulse Jet Filtration

The relevant literature on pulse jet filter theory and applications was assessed to develop coherent guidelines for designing predictive filter models. Observations of several foreign and U.S. researchers not previously subjected to rigorous comparisons showed that there is a considerable unanimity in technical perspectives when data and theories are viewed from a common baseline. Common misconceptions are clarified such as (a) the "air bubble" that descends through the bag during pulsing, (b) dust removal by air flushing rather than by mechanical projection from a rapidly decelerating fabric, and (c) failure to recognize that only a small (1-5 percent) fraction of dust dislodged by pulse action actually reaches the hopper. Data from several sources suggest that not only the compressed air pressure, but also the rate of pressure rise within a bag and the fabric mobility determine dust removal effectiveness. Unique pairings of pressure intensity and dust dislodgeability (as defined by dust/fabric adhesive properties) appear essential for complete removal of surface dust layers. When air jets are correctly placed for specified pulse jet parameters, the surface dust layer should be completely dislodged. Various investigators also suggest that the residual dust (i.e., the irreversibly embedded dust) is relatively constant for fixed dust/fabric combinations. Predictive equations were developed that take into account the major variables seen in the operation of pulse jet collectors. These equations, although designed for single bag units, can be modified for use with conventional multibag, sequentially pulsed units.

CONCLUSIONS

Coal and Fly Ash Properties versus Fly Ash Filterability

With respect to the relationship between coal and fly ash properties and fly ash filterability, an intensive literature review augmented by the determination of size properties and K_2 values for several fly ashes has led to the following conclusions.

Those fly ashes bearing an appreciable net electrostatic charge (based upon qualitative indications only) form a more porous dust layer on the fabric surface. The latter effect would explain the observed reduction in K_2 when S_0 , the specific surface parameter, does not change.

The method of coal-firing, through its impact on the size properties of the fuel entering the combustion zone, also produces a discernible change in K_2 . The much coarser size of the coal charged to the grates of a stoker-fired boiler, as compared to the 70 percent less than 200 mesh feedstock typifying a pulverized coal boiler, was expected to generate a

coarser fly ash and a lower K_2 . However, for the redispersed fly ash samples tested, those from stoker-fired boilers were much more polydisperse and had higher values for S_0^2 , resulting in higher K_2 values for the stoker ashes. After adjustment to a common value of S_0^2 , pulverized coal and stoker ashes showed no statistically significant K_2 differences.

An empirical correlation between ash content and K_2 was displayed, although not at a statistically significant level where it could be used to establish filter system design or operating parameters. Lower K_2 values for high ash coals appear to support the hypothesis that with proportionately less heat available for fusion and breakup of mineral particles or for alteration of their surface properties, a more permeable dust cake is formed.

A strong correlation was observed between fly ash size properties (i.e., particle specific surface) and K_2 , as predicted by theory. It should be noted, however, that with concurrent variations in fuel preparation methods, size reduction processes, and air-to-fuel ratios, fly ash size parameters may show no relationship to parent coal properties. The fact that the equation representing the least squares regression line permits only ± 50 percent estimates for K_2 suggests that many coal fly ashes must share similar values for dust cake porosity and average discrete particle density.

There are a number of factors that mitigate against accurate prediction of fly ash filterability from coal properties alone. First, there may be several unidentified coal properties that exert secondary effects on fly ash filterability. The second order effects may be masked by strong first order parameters, such as the particle size. Because of the data scatter, a large number of samples might be required before the identity and magnitude of such secondary effects could be established with any certainty.

Another factor working against precise quantification of the effects of coal properties on K_2 is the tremendous variability that exists in coals. Coal seam overburdens, partings, and floors (the associated rock structures surrounding and separating the seams) contribute to this variability. Additionally, since coal is formed from diverse plant materials (such that heterogeneity in structure is quite common), extensive compositional variations can occur spatially and in depth for any given seam. This can pose serious problems for coal users with strict specification requirements and also for researchers. While the coal properties obtained from fly ash suppliers represent the best available "average" values, there is no guarantee that the particular fly ash sample received and tested was derived from coal with these same "average" properties.

Mathematical Model for Pulse Jet Filtration

The conclusions presented here are based mainly on the results of several GCA filtration studies with an extensive infusion of experimental data reported by independent researchers.

Single bag tests show that with sufficient energy and the proper introduction of pulse air to a bag, most of the surface dust layer is momentarily dislodged.

Because pulse durations are very brief, ~ 0.1 sec, most of the dislodged dust (90 to 99 percent) is returned immediately to the same or adjacent bags. The amount that descends to the hopper at steady state filtration must equal the dust quantity deposited during the previous filtration period.

Although the amount of dust redepositing (herein referred to as W_c , the cycling layer) may range from 400 to 1,000 g/m², its highly agglomerated state significantly increases its permeability to air flow (about 7 times). Thus, the W_c layer does not present a serious pressure loss penalty, while at the same time providing a uniform cake thickness for efficient particle capture and stable operating pressure loss.

The presence of the cycling layer, W_c , implies that three factors contribute to the overall bag pressure loss: the pressure loss due to the fabric itself, the contribution from the cycling layer, and finally, the pressure loss increase caused by the fresh dust that arrives during the filtration interval.

The present inability to measure accurately the areal density of the cycling layer along with its unique permeability requires a semiempirical approach to modeling. A parameter defined as the effective residual pressure loss, $(P_E)_{\Delta W}$, must be determined for a specific dust-fabric combination and one set of cleaning parameters.

Given only one pressure loss vs. time (or fabric loading) curve from which $(P_E)_{\Delta W}$ can be estimated, the filter designer or user can estimate bag pressure loss for any set of operating conditions that may include variations in inlet dust concentration, filtration velocity, frequency of cleaning, intensity of cleaning as defined by reservoir compressed air pressure, compressed air orifice dimensions, solenoid valve opening time, bag volume, and the temperature, barometric pressure, and density of the filtered air. All predictions, however, apply only to the dust-fabric combination described in the single test.

The modeling equations may be extended to typical multibag, sequentially pulsed field units by iteration processes similar to those used with reverse air or mechanically shaken systems.

SECTION 2

INTRODUCTION

PROGRAM OBJECTIVES

The GCA fabric filtration model as tested in limited field applications has shown good agreement between actual and predicted performance parameters.^{1,2} Therefore, it has the potential to become a useful tool in developing design parameters for new filter systems and/or diagnosing problem areas of existing systems. Optimum model application, however, depends upon accurate determination of the specific resistance coefficients, K_2 , for various fly ashes and the estimation of the degree of fabric cleaning, a_c , provided by the type and intensity of the cleaning process.

The purpose of this study was to provide as broad a data base as possible for estimating two parameters, the specific resistance coefficient, K_2 , and the cleaning parameter, a_c , for a specified fly ash/fabric combination. Both factors play major roles in the existing mathematical model for predicting fabric filter performance.² The present method for predicting K_2 values by means of the classical fluid dynamics relationships discussed in earlier reports provides at best only rough, ~50 percent accuracy. In that the current theory deals only with idealized spherical shapes and depends upon porosity estimates relating to monodisperse distributions and not to the characteristic polydisperse systems encountered with typical fly ashes, the present semiempirical correlations are surprisingly good. However, there are no provisions within current predictive equations to account for the possible impact of the varying properties of coal fly ashes from coals mined at several locations in the U.S.A. and burned in large quantities in pulverized and stoker-fired boilers. The determination of K_2 and a_c values for various fly ashes in conjunction with an assessment of their related coal properties was intended to establish quantitative links with fly ash behavior or at least to establish a data bank for providing improved estimates of the K_2 and a_c parameters.

It was proposed that a representative survey of the chemical, mineralogical, and selected physical properties of coals and their associated seam and rock structures would furnish an insight as to how the resultant fly ashes behave in fabric filter systems. In limited cases, quantitative relationships might be established between coal properties and the associated K_2 and a_c values for different fly ashes. Even when correlations lack the accuracy desired for direct inclusion in the mathematical model, a significant gain will still have been realized because of the many ashes made available for comparison of physical and filtration properties.

METHODOLOGY

The first part of this study was intended to establish how maximum application of the project results might best be made under the program constraint that the ultimate data outputs would depend heavily upon laboratory experiments with some 12 to 15 selected coal fly ashes. It was decided that one of the first activities should be to determine what actions should be undertaken to properly structure the study. These are listed below without regard to priority:

- A detailed survey of the U.S. coal production statistics,
- The projected use of these coals as energy sources where fabric filtration has been or might be adopted for control of particulate emissions,
- The identification of coal properties suspected to affect the filterability of the resultant fly ashes, and
- The locating of the best sources for fly ash samples from cooperating utility and industrial coal users who are now using fabric filters with both pulverized and stoker-fired boilers.

An important step was to develop a rationale for the selection of 12 to 15 different coal fly ashes from a variety of U.S. sources such that the sampling would represent not only the expected impact of coal property variability on fly ash filtration parameters, but also the expected consumption statistics of these coals and the extent to which their particulate emissions might be curtailed by fabric filter systems.

The physical and chemical properties of the selected coals were then related to specific properties of their resultant fly ashes that might directly or indirectly affect their filtration behavior. For example, those chemical constituents of a coal known to determine ash fusion properties were also expected to influence the ultimate size of the particles reaching the filter. As a result, both resistance to gas flow and adhesion characteristics of the dust layer could be altered through changes in the specific resistance coefficient, K_2 , and the cleaning parameter, a_c .

The final phase of this program was to determine K_2 and a_c values for the selected fly ashes by laboratory measurements or through analyses of data reported in the literature so that the physical and/or chemical properties of various coals might be related quantitatively or qualitatively to the overall filterability of the resultant fly ashes.

SECTION 3

TECHNICAL BACKGROUND

COAL PROPERTIES VERSUS FLY ASH SPECIFIC RESISTANCE COEFFICIENT, K_2

Many variables can be cited that might be expected to exert first, if not second, order effects on K_2 . Without preliminary ranking, the following items were proposed as fly ash properties potentially relatable to the properties of their precursor coals.

Particle Shape

As a result of fusion, degassing, or decomposition, most coal fly ashes will display a large population of spherical, sometimes hollow, particles called cenospheres whose discrete particle densities are often lower than those of the parent mineral components. At the same time, however, most quartzitic or other high melting point materials in the feed may retain their characteristic crystalline structures. Generally, spherical particle aerodynamic behavior conforms to that predicted by theory. However, if irregular shapes and micaceous or needle-like materials appear in the ash, they would be expected to alter the characteristic porosity of the dust cake. Additionally, an increase in polarization effects might be anticipated with highly irregular particles in the presence of electric fields.

Particle Density

It is suspected that the effective densities of many spherical particles may vary with diameter. Conversely, many unfused mineral particles in the fly ash (e.g., quartz, clay, iron oxide, unburned coal, and graphite) will retain their characteristic densities. Consequently, any estimates of dust cake porosity deriving from assumed values for average particle densities should be made with caution.

Particle Hardness

The extent to which a given mineral component melts within the furnace will depend in part on the initial particle size, a function of its crushability or hardness. Insofar as the crushing of coal is concerned for pulverized firing (70 percent less than 200 mesh), a soft or relatively fine mineral fraction should lead to a finer product.

On the other hand, the relatively coarse feed used with stoker-firing results in a characteristically coarser fly ash (20 to 50 μ m MMD) according to many field observations. In the case of cyclone boilers, however, a 14 mesh grind actually produces a finer fly ash than that generated by pulverized coal burners because of the greater particle residence time and the inertial separation of the larger particles from the spiraling gas stream.

Surface Properties

Solids with high surface roughness have the capacity to adsorb more of any physically adsorbable gas including moisture. Even in the absence of hygroscopic effects, adsorbed moisture plus the number of surface asperities may affect particle-to-fiber (fabric) adhesion. The stronger the adhesive bonds, the less chance that particles will shift from their initial impact points under the influence of aerodynamic drag. Hence, one might infer that the effect of face velocity (via its impact on particle momentum) would be less with increased moisture adsorption. It is also expected that a more porous cake structure would be less susceptible to gradual compression if the moisture holding were higher. The basis for the above statement is that absorbed moisture strengthens the bonds between particles.

Hygroscopic and Hydration Properties

The calcination products of marble, dolomite, and various clays may absorb so much moisture that the dust deposits on a filter assume a mud-like texture unless gas temperatures are maintained well above the dewpoint. If electrical charge is a factor, the conduction of the ash and/or fabric via its ionic structure may affect significantly the charge leak rate from various fabrics. Chemical reactions within the finely divided fiber structure of the fabric yarns may also promote fabric degradation. Additionally, chemical reactions among the mineral fraction of the ash and the gas phase constituents, such as sulfur and nitrogen oxides and moisture, may cause variations in K_2 .

COAL AND FABRIC PROPERTIES VERSUS FLY ASH CLEANING PARAMETER, a_c

Coal Properties Affecting Both a_c and K_2

Many of the coal properties suspected to affect directly or indirectly the fly ash K_2 values are also expected to determine the ease or difficulty with which a dust layer can be dislodged from the supporting fabric. Size, shape, hygroscopicity, electrical charge characteristics, and chemical reactivity typify particle attributes that may influence particle-to-particle and particle-to-fabric adhesion. Direct and/or electron microscope observation of the selected ash samples, coupled with petrographic and chemical properties, may assist in defining the relevant shape and surface characteristics as well as the probable mineral species.

Generally, the deposition of single particles from monodisperse (highly unlikely) and polydisperse distributions in which the cake porosities are the same will result in increased interfacial contacts, and hence greater adhesion for the finer particle populations. Should appreciable agglomeration take

place between the actual particle sampling location and the time of dust deposition on the filter, however, a significant reduction in contact points per unit area might result. Similarly, should strong electrical repulsion forces be present because of a highly charged homopolar aerosol, the possibility of a more porous dust cake structure should be considered.

It has also been emphasized in prior studies that adhesive forces for any one dust/fabric system are characterized by a range in forces. Furthermore, if a single cleaning step fails to dislodge some of the dust layer, it is highly probable that an appreciable number of its adhesive bonds have been severed. Therefore, whether cleaning be accomplished by bag collapse and reverse flow, mechanical shaking, or high energy jet pulse, the cleaning parameter actually represents an average or resultant adhesive level caused by several successive dust cake perturbations.

Fabric Properties Affecting a_c

Except for differences in surface treatments, the glass fabrics used in prior GCA studies were nearly identical weaves with essentially the same bulk fiber coverage of the filtering surfaces.^{1,2} If it is assumed that differences in fabric properties are not significant, the fact that rough estimates of the cleaning parameters, a_c , for fly ashes filtered at the Sunbury, PA; Nucla, CO; and Bow, NH power plants were nearly the same suggests that the adhesive characteristics of these ashes must have been very similar.² However, the data scatter also indicated that the standard error for these measurements was at least 50 percent.

Given the same fiber dimensions, it is expected that differences in fiber moisture adsorption as affected by surface treatments may contribute to differences in adhesion, particularly in those instances where dew point and condensation problems arise. Fiber geometry and surface and roughness are also expected to affect the contact area at points of adhesion.

One factor expected to play a major role in dust-fabric adhesion is the actual contacting surface at the interface between the dust layer and the fabric. In the case of woven glass (3/1 twill weaves), the normal filtering face consists of 25 percent continuous, multifilament yarns and 75 percent bulked or texturized yarns, the latter providing a much higher fraction of potential dust-to-fiber contact points.^{1,2} The quantity of loose or disengaged fibers present in the surface layer has a significant bearing on adhesion as has been demonstrated by the smaller values of the fly ash cleaning parameter observed during tests with napped sateen weave cotton fabric.¹ Previous measurements on the cotton fabric showed a nearly threefold reduction in the cleaning parameter for an equivalent cleaning energy and the same fly ash used in glass fabric filtration.

Other Factors Contributing to Fabric Cleanability

Estimation of the fabric cleaning parameter, a_c , is a complex process that depends not only upon the unique adhesive force, F_A , between a specific dust and a specific supporting fabric, but also upon the fabric surface dust loading immediately before cleaning, W , and the separating force, F_s , the

latter generated by the acceleration imparted to the dust layer by the cleaning process. In the case of bag collapse and reverse flow cleaning, the product of dust loading and gravitational acceleration (Wg) defines the separating force, F_s .² On the other hand, mechanical shaking creates accelerations, a , in the $5 g_a$ range. Pulse jet cleaning, because of the very high energy inputs, produces accelerations as high as $250g_a$.² Thus, much greater dust separating forces are produced than attainable by gravity forces alone. It should also be noted that a much lower fabric dust loading is required for dust layer separation when greater accelerations are imparted to the dust fabric system.

With the simple collapse and reverse flow cleaning process frequently used with fly ash filtration by woven fabrics, there is also the chance that the radius of curvature of a bag and the rate at which the flow is stopped may influence the amount of dust removal. In the former case, installation of anticollapse rings or decreased bag tensioning will increase local radii of curvatures. Coupled with the rate at which the curvature changes, as determined by damper response to its drive mechanism, the ability of the flexed dust layer to bend with the fabric may also influence the extent of adhesive bond rupture.

COAL SOURCES, PRODUCTION STATISTICS, UTILIZATION, AND PROPERTIES

Survey of U.S. Coal Production and Utilization

The principal objective of this study was to determine how the chemical and physical properties of various coals related to the filtration characteristics of their resultant fly ashes. Because of the high degree of variability in coal properties, it was necessary to group coals within several broad categories that highlighted certain variables or variable combinations suspected to influence the filtration properties of fly ash.

If definitive correlations between coal and/or fly ash properties and fly ash filtration characteristics are indicated, it may be feasible to factor them into the present EPA/GCA filtration model. Conversely, should no apparent correlations be identified, it will probably be necessary to resort to laboratory (or preferably) field measurements of K_2 and a_c to assure successful model applications.

Coal production and use statistics given in Table 1 show the estimated tonnages for lignite, subbituminous, and bituminous coals mined in specific U.S. Coal Regions, Districts, and States that are combusted in utility and industrial energy or steam generating operations. These data, based upon statistics developed by the Department of Energy show that nearly 80 percent of the coal is produced in the eastern and midwestern U.S. whereas current western output accounts for only about 20 percent.³ However, the increase in coal production to supply new, large (~2,000 Mw) power stations in the West is expected to change this balance. It should be noted that the latter region is also a source and major user of lignite in the U.S.

TABLE 1. ESTIMATED COAL PRODUCTION USED BY UTILITIES AND INDUSTRY
FOR ELECTRICAL POWER, STEAM, OR HEATING PURPOSES

	Region, District and/or State	ktons/yr ^a	Percent of total production	
			Region	District
I	Northern Appalachian Region	140,616	26.2	
	1 - Eastern Pennsylvania Pennsylvania (E) Maryland West Virginia (NE)	43,384		8.1
	2 - Western Pennsylvania	15,534		2.9
	3 - Northern West Virginia	29,091		5.4
	4 - Ohio	45,212		8.4
	5 - Michigan	---		0.0
	6 - West Virginia Panhandle	7,395		1.4
II	Southern Appalachian Region	120,662	22.5	
	7 - Southern Numbered 1 Virginia West Virginia (S)	5,361		1.0
	8 - Southern Numbered 2 Kentucky (E) Tennessee (N) Virginia West Virginia (S)	115,261	21.5	
III	Alabama Region			
	13 - Southeastern Alabama Georgia Tennessee (S)	13,871		2.6

(continued)

TABLE 1 (continued)

	Region, District and/or State	ktons/yr ^a	Percent of total production	
			Region	District
IV	Eastern Midwest Region	132,044	24.6	
	9 - West Kentucky	52,517		9.8
	10 - Illinois	54,336		10.1
	11 - Indiana	25,191		4.7
V	Western Midwest Region	24,518	4.6	
	12 - Iowa	613		0.1
	14 - Arkansas - Oklahoma Arkansas Oklahoma (E)	268		0.1
	15 - Southwestern Kansas Missouri Oklahoma Texas	23,637 4,002 6,000 3,635 14,000		4.4
VI	Western Region	104,881	19.5	
	16 - Northern Colorado	274		0.1
	17 - Southern Colorado Colorado New Mexico	6,385		1.2
	18 - New Mexico Arizona New Mexico	19,238		3.6
	19 - Wyoming Idaho Wyoming	30,774		5.7
	20 - Utah	6,206		1.1

(continued)

TABLE 1 (continued)

Region, District and/or State	ktons/yr ^a	Percent of total production	
		Region	District
21 - North-South Dakota	10,935		2.0
22 - Montana	26,204		4.9
23 - Washington	4,795		0.9
Alaska			
Washington			
Total Production	536,500 ^b		

^aShort tons/yr. 1 short ton = 0.907 metric tons.

^bElectric Utilities usage estimated at 89 percent of total production.³

Figure 1 shows the geographical distribution of major U.S. coal fields, the types of coals mined, and also the location of potential fly ash sources among utility and industrial coal consumers. Given no other guiding information, it would seem unreasonable to base the number of fly ash samples from each region, district, or state upon their respective coal consumption rates.

Identification of Coal Producing Areas and Key Properties of Coals Used for Energy Generation

Coal Producing Areas--

In Table 2, principal mining areas are identified with respect to state, district, county, and common names for the coal fields and seams as given in the Keystone publications.^{4,5} The coal district numbers are those cited in a joint DOE/EIA document.³ To reduce the scope of the selection effort, data are presented only for the major coal mining counties whose cumulative production accounts for 75 to 95 percent of the total state production when listed on the basis of decreasing production rates. Thus, the average or typical coal properties shown for the various counties are as good a representation for the region as can be developed for any single set of analyses.

Proximate Analyses and Sulfur Content--

The proximate analyses, which describe those properties used to assign coal rankings, do not include those factors believed to affect directly fly ash filterability via their impacts on K_2 or a_c . However, in the case of stoker-fired boilers, the caking properties of the coal burning on the grate may determine the ultimate distribution of the mineral components between fly ash and bottom ash. Additionally, even with no alteration of filtration characteristics per se, the moisture and ash content can affect significantly the uncontrolled emission levels and, in turn, the design capacity and frequency of cleaning of a baghouse. It is also possible that the fuel composition with respect to moisture, ash, volatiles, and fixed carbon may have some bearing on the ultimate size of those mineral constituents not intrinsically bound to the coal (over-burden, partings, and floor) that pass through the pulverizers. As ash content increases, it is suspected that less heat may transfer to the particles for a fixed energy input, thus slowing the particle transition to the viscous and fluid states. The result should be a coarser fly ash as reported by Horney,⁶ although he attributes the coarser size to the large amount of extraneous minerals found in high ash coals. In low ash coals, the intrinsic mineral content, i.e. that fraction intimately mixed with the coal and usually composed of much smaller particles, represents a large fraction of the total ash content.

Approximate average values for volatile matter, sulfur, ash, and moisture contents for the six coal producing regions are shown in the Figure 2 bar graph. Despite the broad range in coal analyses with some of the variability relating to mining, cleaning, and assaying techniques (as received or dry basis), three general coal groups are discernible. Eastern coals represented by Regions I through III appear to be characterized by medium to high volatile content, ~2 percent sulfur, low (6 to 8 percent) ash, and low moisture (4 percent). Midwestern coals, Regions IV and V, show high values for all the

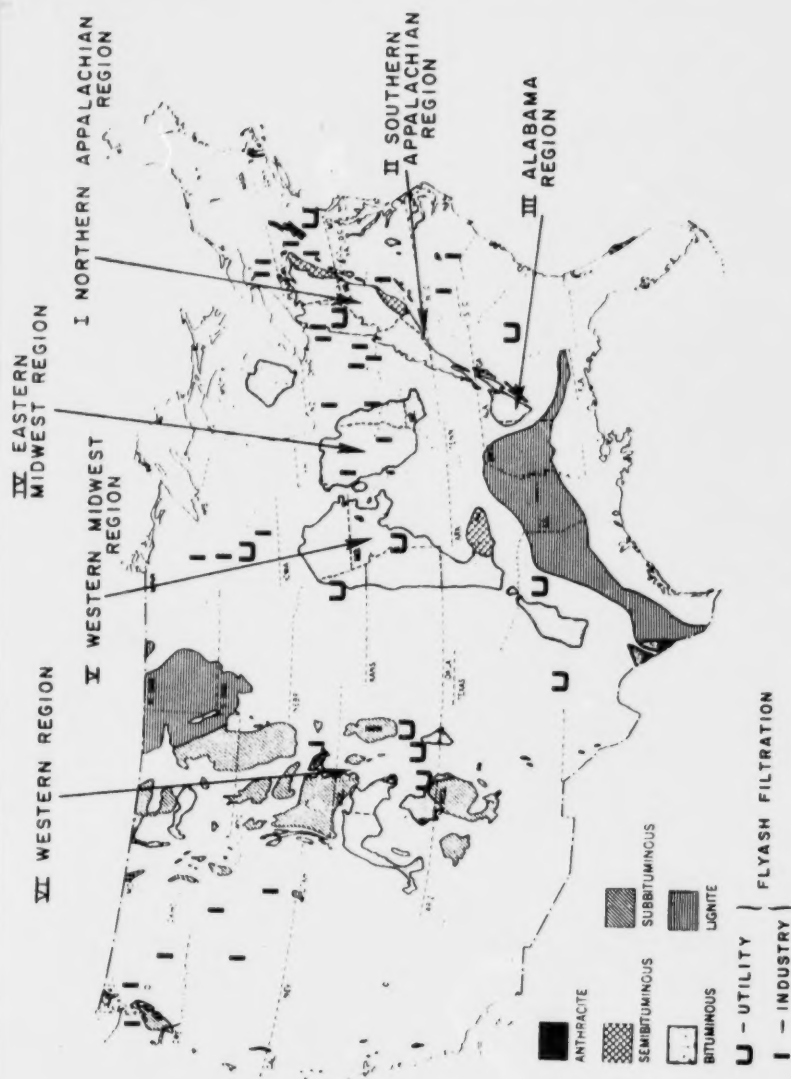


Figure 1. Major U.S. coal producing regions and distribution of coal-burning utilities and industries using fabric filters.

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TABLE 2. DISTRIBUTION AND PROPERTIES OF TYPICAL U.S. COALS (LIGNITE TO BITUMINOUS) WITH ESTIMATED FRACTIONS USED FOR POWER GENERATION PURPOSES

[illegible]

(continued)

TABLE 2 (continued)

District code ^a	Mine location State or District and Seam or Field	County	Keynote ^b reference (M) or (S)	Percent of total production ^c	Coal properties						Coal properties	Comments
					Moisture %	Volatile matter %	Fixed carbon %	Ash %	Sulfur %	Heating value Btu/lb.		
III	Alabama Region			2.6								
13.	Southeastern Alabama			2.6								
	Alabama Creek	Jackson	448 (N)		1.0	11.6	62.1	3.3	0.7	14,110	District 13	Alabama - shale, sandstone, fireclay slate.
	Jefferson	Jackson	449 (N)		2.3	11.9	58.5	7.3	1.1	13,780		
	American	Baker	448 (S)		2.3	32.5	52.9	12.3	1.6	12,550		
	Georgia				3.1	27.6	64.6	4.7	0.8	14,398		
	Dade Seam	Dade	481 (N)		See Southern Numbered 2							
	Tennessee (S)	Marion	559 (N)		2.8-6.3	23.2-29.3	60.6-65.4	4.7-13.4	0.4-1.4	12,830-		
	Dade Seam									14,390		
	Sewanee Seam	Hamilton	560 (N)		2.0-3.3	28.6-31.0	51.6-60.9	7.8-16.5	1.7-2.7	12,160-14,150		
IV	Eastern Midwest Region			24.6								
9.	West Kentucky No. 11 Seam	Muhlenberg	509 (N)	9.8	8.2	36.7	44.3	8.8	3.3	11,900	District 9	Eastern Midwest Region - shale, slate, fireclay limestone
	No. 9 Seam	Union	510 (N)		5.0	39.8	49.7	10.5	3.15	12,940		
	No. 4	Hopkins	510 (N)		9.9	36.3	47.5	5.8	2.4	13,310		
10.	Illinois No. 5 Seam	Peoria	491 (N)	10.1	15-19	32-35	37-43	8-13	2-4	9,800-	District 10	
	No. 6 Seam	Fulton	490 (N)		16-20	31-35	37-40	8-13	3-5	10,700-		
	No. 7 Seam	Danville Vermillion	492 (N)		13-17	37-39	37-40	9-11	3	10,500-11,300		
11.	Indiana Springfield Coal V Surrant IV Danville VII	Several counties	495 (N) 495 (N) 495 (N)	4.7	10-0 16-4 12.6	41.2 34.2 35.4	39.4 43.1 39.8	9.3 8.4 12.2	3.31 1.16 2.03	11,590 11,160 10,900	District 11	
V	Western Midwest Region			4.6								
12.	Iowa Lower Ford Seam		141 (S)	0.1	9.6	38.1	38.3	13.6	7.3	12,130		
14.	Arkansas-Oklahoma Lower Hardstone Iron Point	LeFlore Craig	541 (N) 541 (N)	0.1	2.9 2.0	17.8 45.5	72.3 46.9	7.1 5.7	0.8 3.3	14,000 13,744		District 14 - black shale, dark gray shale, limestone.
15.	Southeastern Kansas Several Seams	Bourbon	503 (N)	4.4	2.5-11.1	38.6-41.1	47.8-54.2	9.4-17	1.6-4.5	11,330-	Kansas	Kansas - limestone, high germanium.
	Severnall Seams	Cheerokee Crawford	503 (N) 503 (N)		2.2 3.3	39.7 44.4	50.2 45.5	10.2 10.0	3.9 4.4	13,550 13,570		
	Missouri Tebo Seam	Linn	276 (S)		9.9	41.4	42.5	15.9	6.4	11,910	Missouri	
	Bevier Seam	Macon	276 (S)		12.1	39.1	46.3	14.4	5.0	12,070		Missouri - shale, sandstone, clay parting.
Oklahoma				See Arkansas-Oklahoma								
Texas Jackson ^e Yegua ^f Bull Creek			362 (N) 562 (N) 563 (N)		40.5 36.1 13.4	24.2 27.4 36.1	16.4 19.8 29.4	18.9 16.7 21.1	1.2 1.0 3.4	4,872 5,975 8,595	Jackson-Yegua	Lignite Lignite
											Bull Creek	Volatiles high, sulfur high, ash high, moisture medium.

(continued)

TABLE 2 (continued)

District code ^a	Mine location		Keystone ^b reference page	Percent of total production ^c	Coal properties							Geology of seam overburden, partings, and floors
	State or District and Seam or Field	County			Moisture %	Volatiles matter %	Fixed carbon %	Ash %	Sulfur %	Heating value Btu/lb	Coal properties	
VI	Western Region			19.5								
16.	Northern Colorado			0.1								
	Yampa Field	Noffat	461 (M)		8.0	37.4	45.9	9.0	0.5	11,203	District 16	District 16 - shale, sandstone, siltstone, claystone.
	North Parkfield	Jackson	461 (M)		14.9	35.0	41.5	8.6	0.4	9,903	Sulfur low, ash medium.	
17.	Southern Colorado			1.2								
	Allen Seam	Los Animas	63 (S)		4.0	34.3	44.3	21.3	0.4	11,740	District 17	District 17 - See District 16.
	New Mexico				See New Mexico District (Colfax)						Volatile high, sulfur low, ash high, moisture low.	
18.	New Mexico			3.6								
	Frutland Field	San Juan	529 (M)		10.7	35.9	38.1	15.0	0.86	10,200	District 18	District 18 - shales, siltstone, seashore sediments.
	Raton Seam	Colfax	286 (S)		1.7	35.0	50.8	14.1	0.6	12,920	Volatile high, sulfur low, ash medium to high, moisture medium	
	Arizona											
	Blue Seam	Navajo	46 (S)		11.8	41.9	50.7	7.3	0.7	12,580		
	Blue Seam	Navajo	46 (S)		11.2	42.2	49.1	8.6	0.4	12,370		
19.	Wyoming			5.7								
	Rock Springs	Sweetwater	655 (M)		11.1	42.2	53.4	4.3	0.9	13,250	District 19	District 19 - See District 16. Note: Ca and Na may be unusually high.
	No. 7 Seam											
	Rock Springs											
	No. 7 1/2 Seam											
20.	Utah			1.1								
	Subseam No. 3 Seam	Sweetwater	656 (M)		14.9	42.9	52.7	4.4	1.0	13,030	District 20	District 20 - shale, sandstone
	Blind Canyon Seam											
		Carbon	450 (S)		4.3	46.5	46.3	7.1	1.2	13,490	Volatiles high, sulfur low to medium, ash low, moisture low.	
		Emery	451 (S)		4.8	44.6	48.0	7.2	0.4	13,590		
21.	North-South Dakota			2.0								
	Hagel Bed	Mercer	536 (M)		37.9	26.7	29.2	6.2	0.6	5,960	District 21	District 21 - clay
		Oliver								7,487	Volatiles high, sulfur low, ash low, moisture high	Note: Lignite
22.	Montana			4.9								
	Dietz No. 1 & 2 Seams	Big Horn	282 (S)		20.6	39.7	54.8	5.5	0.6	12,460	District 22	
	No. 5 Seam	Musselshell	283 (S)		9.8	38.7	48.1	11.1	0.4	11,550	Volatiles high, sulfur low to high, ash low	
	Roundup Seam	Rosebud	284 (S)		11.9	35.5	54.3	10.0	0.5	12,460	low to high, moisture medium to high	
23.	Washington			0.9								
	Bellingham Seam	Whatcom	516 (S)		6.9	38.4	45.2	16.2	0.3	11,420		

^aCode Number used to designate coal districts, Reference 3, DOE/EPA-0118/1(76).

^bM refers to Reference 5, S refers to Reference 6.

^cState, District, or Region production compared to total U.S. production.

^dReference 7, p. 9-3, Table 9-1.

^eLignite.

NOTE:

Arbitrary Rankings-Percent		
	Low	High
Volatiles	20.0	21.0-30.0
Sulfur	1.2	1.3-1.9
Ash	8.0	9.0-13.0
Moisture	7.0	8.0-12.0

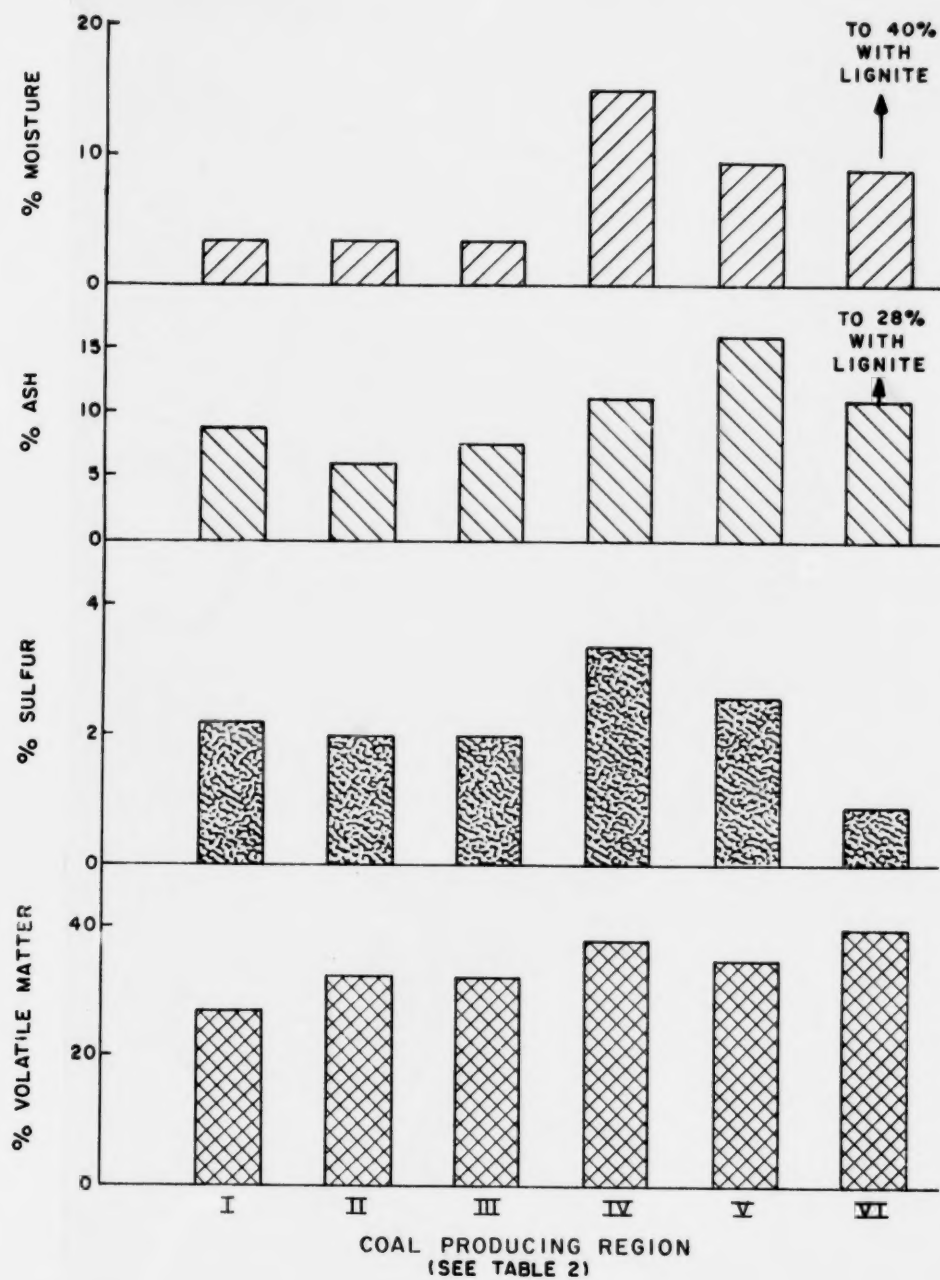


Figure 2. Estimated coal analyses, regional basis.^{4,5}

above descriptors. Because of the high ash and moisture levels for midwestern coals, the heating values are usually lower while the high sulfur content adds to the overall emissions control problem.

In the case of western, Region VI, coals, sulfur contents are consistently low, the volatile content high, and with the exception of lignites, the ash and moisture contents parallel those for midwestern coals. The fact that ESP systems generally perform less efficiently (or at least are more expensive for low sulfur coals) suggests that the filtration option may be the better approach with many western coals.

Mineralogy of Coal Seam Overburdens (Roofs), Partings, and Floors

Whenever possible, an attempt was made to establish the composition of the rock structure surrounding or dividing the coal seams to see what relationships existed between the unfired mineral composition of the coals and the final chemical assay of the resultant fly ashes. Inspection of Table 3 indicates that the similarities among the mineral fractions of most coals far outweigh the differences. With regard to potential relationships anticipated for various mineral constituents, it was expected that a sandstone, because of its high SiO_2 content, might yield coarser particles after pulverizing. Grindability indices (ASTM-D409) also provided a measure of how coal (and mineral) hardness properties affect a B&W pulverizer product, Figure 3. Horney has reported that, inexplicably, the finer the pulverizer product from high dolomite western coals, the larger the resultant fly ash.⁶ Ordinarily, one expects the softer mineral constituents to yield a finer crusher product. Additionally, the high SiO_2 fusion temperature suggests that the formation of spherical fusion products (cenospheres) is less likely. Aside from indicating a more friable material, the presence of limestone or dolomites may afford more reactivity with respect to SO_2 removal via SO_2 scrubbers as reported, for example, at the Merrimack Station of Kansas City Power and Light.⁷ Any significant in-situ capture of SO_2 by calcined alkali metals (Ca, Mg, Na, and K) can produce hygroscopic sulfite, bisulfite, and sulfate salts in the ash. Considerable discussion has been devoted to the high sodium contents of certain Wyoming coals that appear to improve ESP collection because of reduced electrical resistivity.⁸ However, the same attribute might conceivably prove a disadvantage (high pressure loss) if it led to increased moisture content in a filter cake even though it would enhance the capture of SO_2 or other acid gases..

Further details on coal mineralogy factors are presented in Table 3. Typical minerals are identified with the common geological materials making up the "rock" phase of "as mined" coals as distinguished from the organically-bound, intrinsic compounds contained in the flora from which coals were formed. The relative hardness, chemical stability, and melting properties that are expected to affect particle size properties, chemical activity and hygroscopicity of the fly ash are listed for the more common minerals along with the conventional analyses as oxides of the acid and basic constituents appearing in typical coals.

TABLE 3. COMMON MINERAL CONSTITUENTS OF COAL SEAM FLOORS, PARTINGS AND OVERBURDENS:
CHEMICAL COMPOSITION AND PHYSICAL PROPERTIES

Rock name	Mineral name	Conversion (C) Decomposition (D) or Melting (M) Temperature °C	Hardness Moh scale	Elemental composition as oxides, percent												Dolomite ratio CaO + MgO			
				Volatile components	Basic components					Acid components				Cumulative Percent basic	Percent acidic		Base/Acid ratio		
					C	H	Ca	Mg	Na	K	Fe	Si	Al					Ti	S
1. Claystone (consolidation of block like structures with no parallel alignment - mainly clays and mica) See shales for composition.				5.0	1.3	5.5	1.2	0.4	1.3	1.4	78.7	5.0	9.8	83.7	0.117	0.684			
2. Sandstone																			
a. Quartz	a (low) quartz β (high) quartz Cristobalite Calcite CaCO ₃ Dolomite CaCO ₃ ·MgCO ₃	C 573° to 8 (high) quartz C 867° to Cristobalite M 1713° D 900° D 900°	7 7 7 3 3.5-4.0	5.0	1.3	5.5	1.2	0.4	1.3	1.4	78.7	5.0	9.8	83.7	0.117	0.684			
b. Limestone	Calcite CaCO ₃	D 900°	3			100.0										1.00			
	Dolomite CaCO ₃ ·MgCO ₃	D 900°	3.5-4.0			58.2	41.8									1.00			
3. Shales				2.6	5.0	3.1	2.4	1.3	3.2	6.5	58.1	15.4	16.5	73.5	0.225	0.33			
a. Limonite	Limonite 2Fe ₂ O ₃ ·3H ₂ O	D 500°	4.0-5.5																
b. Mica plates	Illite (Hydrous K, A Silicate)	C 1000° to orthoclase M.P. of 1100°C																	
c. Quartz	See Sandstone																		
d. Clay(s)	Kaolinite (Al ₂ Si ₂ O ₅ (OH) ₂) Montmorillonite (OH) ₂ Al ₂ Si ₂ O ₇ ·2 H ₂ O	2.0-2.5 2.0-2.5																	
e. Feldspar	Orthoclase K ₂ O·Al ₂ O ₃ ·6SiO ₂ Albite Na ₂ O·Al ₂ O ₃ ·6SiO ₂ Anorthite CaO·Al ₂ O ₃ ·6SiO ₂	M 1100°C	6																
4. Slate	Final state of shale	See shales		2.6	3.7	3.1	2.4	1.3	3.2	6.5	58.4	15.5	0.6	16.5	74.5	0.221	0.33		

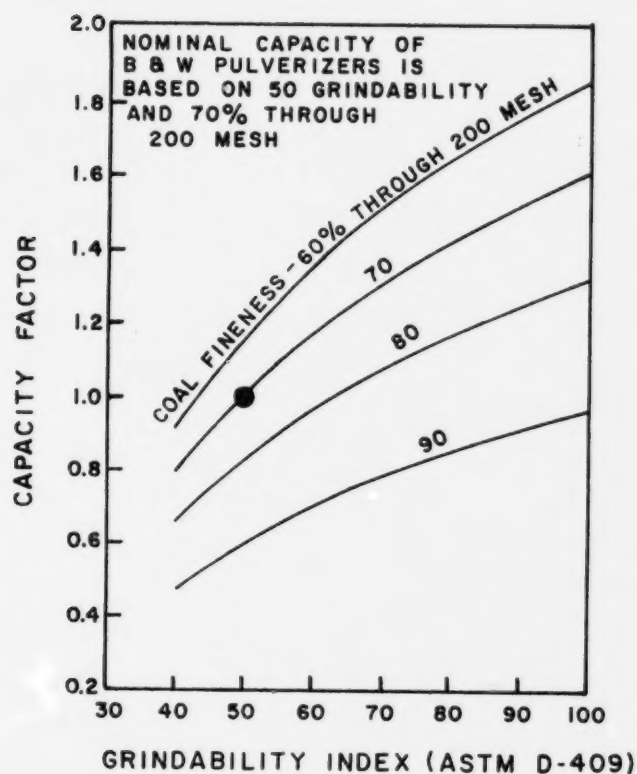


Figure 3. Effect of grindability and fineness on pulverizer capacity.

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Average analyses for claystone, shale, and slate are approximately the same. They differ significantly from that for sandstone which is predominantly siliceous in nature and often accompanied by calcite and dolomite. The special descriptors such as the Base/Acid or Dolomite Ratios also differ significantly as noted for the respective sandstone and shale (also slate and claystone) values.

Coal Firing Method

The method of coal firing was expected to influence fly ash size properties in two ways. First, the degree of size reduction prior to firing determines the parent size of the mineral constituents of the coal; i.e., that fraction of the inorganic solids originating from the coal seam overburden, parting or floor minerals. In the case of pulverized coal-fired boilers, the typical aerosolized material is described as 70 percent by weight less than 200 mesh ($\sim 74 \mu\text{m}$). Cyclone boilers ordinarily fire a coarser grind, 4-14 mesh, whereas stoker coals are only crushed sufficiently to permit uniform grate loadings via the charging mechanism. As shown by Figure 3, grindability and method of firing are frequently interrelated.

If the initial size reduction process were the controlling factor, the ash from a pulverized coal firing system would be the finest followed by the cyclone boiler and stoker-fired products, respectively. As stated earlier, exceptions have been reported with respect to the fineness of crushing and the size of the fly ash. However, the added inertial separation feature of a cyclone boiler produces a fly ash effluent even finer than that generated by pulverized coal firing. In the case of stoker-fired systems, the actual fly ash classed as the uncontrolled effluent is not only the coarsest but also apt to contain more unburned coal than the other effluents. These size trends are shown by the rough estimates of size listed in Table 4.9,10,11. More recent size reportings for the same firing systems are indicated in Figure 4.12. As expected, the use of fly ash re-injection with spreader stokers results in a somewhat finer ash. However, size parameters for the pulverized coal-fired boiler ash are unusually high compared with the 4.8 to 20 μm MMD values cited in Table 4.9-11. At this time, the relationship between fly ash size and firing method appears to be qualitative only due to the difficulties in making such measurements and variations in system geometries, particulate residence time in the system, and settlement factors. However, it is important that the firing method be taken into account along with the several factors cited previously that are believed to affect the ultimate filterability of coal fly ash.

Chemical Constituents of U.S. Coals

A comprehensive listing of chemical assays and ash fusibility characteristics for U.S. coals from mainland U.S. coal-producing regions is given in Table 5.13. These data provided the basis for a subsequent evaluation of the impact of ash chemistry on ash fusion properties, the latter expected to influence fly ash size properties. Numerical values for a special parameter describing the relative proportions of certain chemical constituents, the Base-to-Acid-Ratio (B/A), has been computed as an addendum to Table 5. In the next section, the B/A ratio and other special characterizing ratios are examined with respect to potential relationships to fly ash size properties.

TABLE 4. REPORTED MASS MEDIAN DIAMETERS (μm) FOR PARTICULATE EMISSIONS FROM VARIOUS COAL-FIRED FURNACES

Furnace type	Mass median diameter, μm		
	Combustion Engineering Inc. ⁹	MRI ¹⁰	AP-24 ¹¹
Cyclone	4.5	5	2.1 to 4.7 2.1 avg.
Pulverized	11	20	4.8 to 5.7
Spreader stoker	68	48	34 to 420
Underfeed stoker	--	16	--
Traveling grate stoker	--	67	--
Stoker-fired	--	17 to 68 51 arith. mean	--

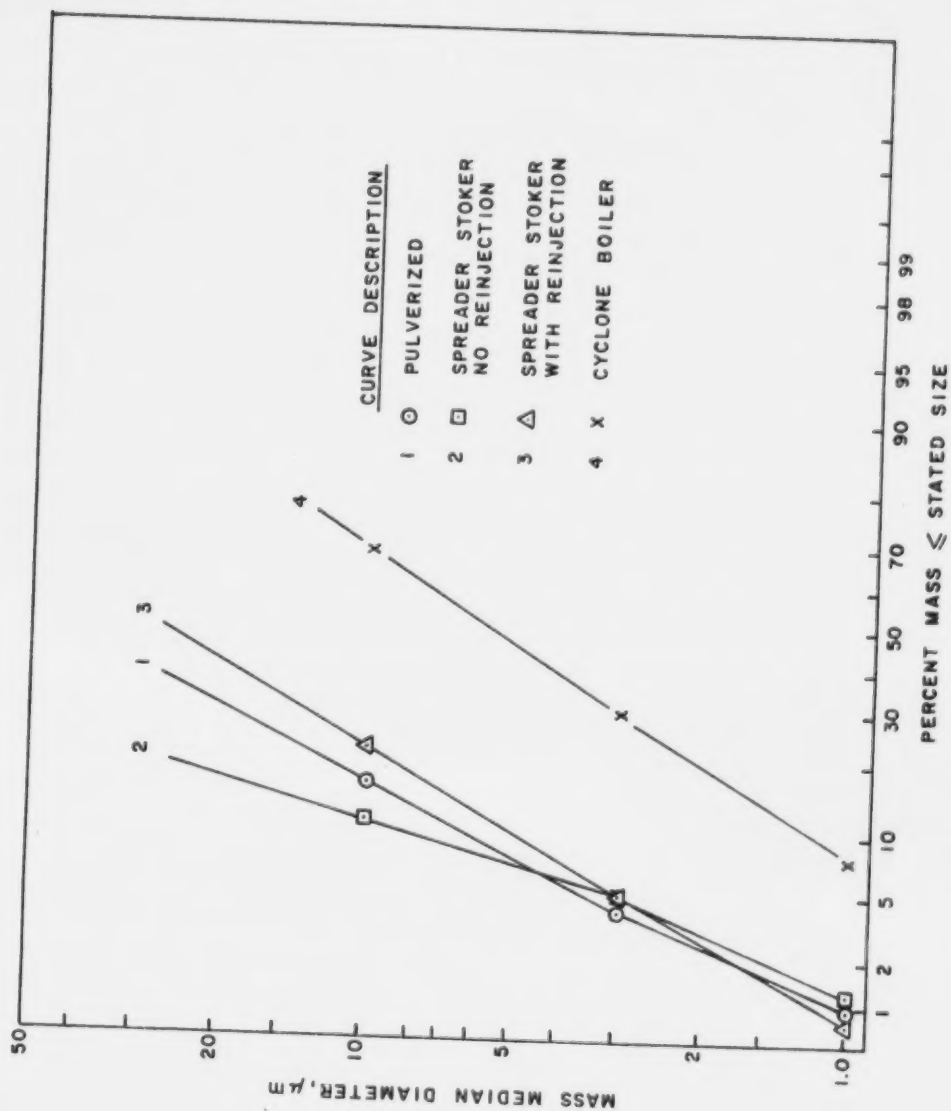


Figure 4. Fly ash mass distributions vs. method of coal firing.¹²

TABLE 5. CHEMICAL CONSTITUENTS AND FUSION PROPERTIES OF U.S. COALS¹³

County and bed	Sample No.	Percent of moisture-free coal		Analysis of ash, percent											Fusibility of ash			Base/acid ratio
				Ash	Sulfur	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	TiO ₂	P ₂ O ₅	CaO	MgO	Na ₂ O	K ₂ O	SO ₃	Initial deformation temperature, ° F	Softening temperature, ° F	
		ALABAMA																
Jefferson:																		
Clements, top.....	1	13.6	3.8	38.4	22.2	35.6	1.1	0.12	1.7	0.8	0.2	2.2	0.6	2,080	2,130	2,300	0.66	
Clements, bottom.....	2	6.9	1.6	45.2	23.5	25.9	1.0	.17	1.8	.9	.2	2.6	.6	2,100	2,180	2,480	0.45	
Clements, middle.....	3	8.5	1.7	45.4	24.9	22.8	1.2	.08	1.8	1.7	.2	4.0	.9	2,160	2,260	2,360	0.43	
Mary Lee.....	4	11.7	.9	53.1	31.1	7.0	1.8	.41	1.8	1.7	.3	2.5	.6	2,910+	-	-	-	
Pratt.....	5	7.0	1.7	42.7	29.3	19.2	1.0	.46	3.3	.6	.3	1.4	1.7	2,520	2,620	2,680	0.34	
Marion: Black Creek.....	6	5.2	1.1	45.2	24.9	15.6	.8	.31	3.8	1.9	.3	2.4	3.6	2,310	2,380	2,600	0.34	
Shelby: Montevallo.....	7	7.3	.8	35.4	19.8	17.9	.6	.06	12.4	2.4	.2	2.8	7.4	2,080	2,130	2,180	0.64	
Tuscaloosa:																		
Brookwood.....	8	17.0	1.2	51.0	33.3	7.6	1.3	.28	1.7	1.5	.2	2.8	.6	2,910+	-	-	-	
Clements.....	9	4.5	1.3	42.3	27.4	20.4	.6	.10	1.9	1.4	.2	3.2	2.1	2,150	2,250	2,390	0.39	
Milldale.....	10	5.3	1.0	48.2	28.4	15.1	1.4	.13	1.8	.8	.3	1.2	2.4	2,600	2,680	2,780	0.25	
Walker:																		
Black Creek.....	11	5.5	2.8	23.9	18.4	45.0	.8	.13	3.4	.8	.3	.9	4.7	2,020	2,150	2,530	1.16	
Cobb.....	12	11.0	2.2	43.7	27.9	21.4	1.3	.12	1.7	1.3	.3	2.5	1.6	2,260	2,400	2,600	0.37	
Mary Lee.....	13	14.5	.8	34.0	32.5	5.3	1.2	.57	1.7	1.0	.5	2.2	.9	2,910+	-	-	-	
ARKANSAS																		
Johnson: Lower Hartsborne....	14	4.0	-	25.2	27.4	20.3	1.3	1.3	7.4	6.4	2.1	1.2	10.3	2,170	2,300	2,500	0.66	
Logan: Paris.....	15	12.5	2.5	24.4	12.1	26.5	.6	.82	18.8	5.6	.8	1.3	10.0	2,180	2,240	2,300	1.43	
COLORADO																		
Freewont:																		
Unknown.....	16	15.9	0.4	53.9	23.4	5.3	1.1	0.01	8.5	0.9	0.4	0.2	6.6	2,370	2,480	2,580	0.19	
Do.....	17	8.6	.6	46.6	21.1	7.9	1.0	.05	9.4	1.2	.1	.1	11.8	2,260	2,360	2,480	0.27	
Do.....	18	6.4	.7	48.9	15.2	6.8	1.1	.04	11.3	.9	.2	.2	14.9	2,150	2,260	2,440	0.30	
La Plata:																		
Unknown.....	19	5.2	1.1	47.7	30.9	11.9	1.4	.13	5.3	.6	.4	.2	1.8	2,490	2,560	2,630	0.23	
Do.....	20	6.0	.6	60.5	26.1	6.0	1.4	.04	1.8	.4	.2	.3	.3	2,910	2,910+	-	0.09	
Las Animas:																		
Unknown.....	21	9.2	.6	48.2	28.2	8.7	1.4	2.8	4.8	1.6	.3	.2	2.4	2,560	2,680	2,770	0.30	
Do.....	22	19.2	.6	71.8	21.8	3.2	1.6	.08	.4	.4	.2	.3	.2	2,910+	-	-	-	
Mesa:																		
Unknown.....	23	13.2	.9	50.0	33.3	4.1	1.2	.43	5.9	.5	1.8	.6	1.5	2,750	2,850	2,910+	0.15	
Do.....	24	12.3	.6	47.7	34.2	3.3	1.4	.30	8.2	2.9	1.0	.2	1.7	2,710	2,740	2,840	0.19	
Hoffat: Unknown.....	25	3.0	.4	34.8	22.7	6.0	1.7	.38	12.8	2.0	3.0	.3	15.1	2,330	2,430	2,510	0.41	
Montrose: Unknown.....	26	11.9	.9	56.6	34.2	5.1	1.6	.02	1.8	.6	.2	.8	.8	2,910+	-	-	-	
Mont: Wadga.....	27	8.5	.8	48.4	30.6	4.7	1.2	1.5	4.6	1.5	.2	.6	4.8	2,840	2,910+	-	0.14	
ILLINOIS																		
Fulton: No. 5.....	28	10.6	3.3	51.7	15.7	16.3	0.6	0.06	8.9	0.8	0.5	2.0	2.8	1,940	2,040	2,230	0.42	
Henry: No. 6.....	29	7.7	3.2	41.4	20.3	23.3	1.5	.06	6.8	1.3	.5	2.1	2.4	1,980	2,020	2,110	0.54	
Jackson: No. 6.....	30	8.3	2.4	49.3	22.3	19.5	1.2	.06	1.7	.8	.4	2.2	1.0	2,130	2,180	2,470	0.34	
Kankakee: Nos. 2 and 5.....	31	6.5	2.7	36.0	20.5	35.4	1.0	.11	1.8	.8	.6	1.8	1.2	1,940	2,050	2,310	0.70	
Peoria: No. 6.....	32	8.1	3.0	42.7	23.2	23.9	.7	.11	3.4	.9	.3	2.3	.8	2,000	2,130	2,220	0.46	
Randolph: No. 6.....	33	17.1	4.8	46.6	19.3	20.8	.8	.24	7.7	.9	.2	1.7	2.4	1,980	2,060	2,360	0.47	
Saline: Davis.....	34	12.7	4.5	42.5	18.5	34.8	.9	.20	1.7	.4	.1	1.8	1.0	2,080	2,130	2,180	0.62	
Schuyler: No. 5.....	35	10.3	3.6	48.0	14.7	18.7	.6	.44	10.4	.6	.2	1.8	2.1	1,940	2,000	2,230	0.50	
Stark: No. 6.....	36	8.9	3.1	42.1	20.1	22.8	1.1	.15	6.6	1.1	.5	1.9	2.0	2,100	2,150	2,360	0.52	
Vermilion: No. 7.....	37	9.1	3.0	45.8	20.2	20.0	1.0	.03	6.1	1.3	.6	2.3	2.2	2,020	2,080	2,320	0.45	
Williamson: Davis.....	38	11.2	3.2	54.5	15.4	21.1	1.0	.27	1.7	.9	.2	2.6	1.1	2,070	2,100	2,410	0.37	
INDIANA																		
Clay: No. III.....	39	7.2	4.0	36.4	20.3	31.8	0.8	0.22	6.1	0.6	0.3	1.5	1.8	1,990	2,040	2,140	0.69	
Greene:																		
No. IV.....	40	7.8	1.4	46.7	31.6	12.8	1.2	.59	1.8	1.2	.3	3.3	.4	2,620	2,700	2,790	0.28	
No. V.....	41	8.7	2.8	51.7	25.3	15.9	1.2	.03	1.8	1.0	.3	2.4	.6	2,470	2,570	2,680	0.27	
Knox:																		
No. V.....	42	9.2	3.4	47.6	23.6	15.5	1.1	.10	3.2	.8	.9	2.9	1.0	2,180	2,290	2,540	0.29	
No. VI.....	43	10.2	2.7	53.6	21.6	17.0	1.0	.09	1.7	1.1	.4	3.7	.4	2,260	2,440	2,730	0.32	
Owen: Upper Block.....	44	7.6	2.6	51.9	25.4	17.5	1.2	.27	1.8	.7	.2	1.7	.4	2,260	2,470	2,570	0.28	
Pike: No. V.....	45	9.1	3.1	42.9	22.3	29.3	1.1	.18	1.9	.6	.2	2.0	.6	2,010	2,110	2,430	0.32	
Sullivan:																		
No. VI.....	46	9.1	2.5	47.9	22.5	21.4	1.2	.10	1.7	.9	1.1	2.6	.9	2,050	2,140	2,290	0.40	
No. VII.....	47	9.7	.7	60.9	25.4	7.0	1.3	.02	1.8	1.5	.3	3.1	.2	2,520	2,680	2,800	0.15	
Vigo:																		
No. V.....	48	14.0	4.5	49.1	16.9	23.0	.9	.11	4.3	.7	1.0	2.0	2.2	1,930	2,020	2,310	0.46	
No. VI.....	49	10.0	4.4	30.7	16.1	40.7	.8	.07	7.9	.5	.2	1.3	1.9	1,900	2,000	2,430	0.94	
No. VII.....	50	6.1	1.1	55.2	26.5	9.5	1.2	.04	1.7	1.2	.3	2.7	.4	2,540	2,640	2,720	0.17	
Harrick: No. V.....	51	12.4	4.2	35.4	18.6	27.7	1.0	.06	8.4	.6	.4	2.4	3.1	2,050	2,110	2,230	0.62	

TABLE 5 (continued)

County and bed	Sample No.	Percent of moisture-free coal		Analysis of ash, percent										Fusibility of ash			Base/acid ratio
														Initial deformation temperature, ° F	Softening temperature, ° F	Fluid temperature, ° F	
Ash	Sul- fur	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	TiO ₂	P ₂ O ₅	CaO	MgO	Na ₂ O	K ₂ O	SO ₃						
NEW MEXICO																	
Colfax: Yankee.....	97	12.6	0.6	57.4	30.0	6.7	1.2	0.07	1.7	2.0	0.1	1.0	0.5	2,880	2,910+	-	0.13
McKinlay: Axtac.....	98	16.3	1.1	61.9	22.9	7.8	.8	.01	3.2	1.5	.7	1.1	2.1	2,420	2,470	2,570	0.17
Rio Arriba: Unknown.....	99	10.9	3.2	47.2	20.4	27.3	1.0	.06	4.3	.8	.3	.2	.6	2,170	2,230	2,570	0.48
Sandoval: Kaseman.....	100	5.9	1.5	28.9	14.3	22.1	.9	.12	11.2	4.2	.5	.2	17.3	2,020	2,080	2,210	0.87
San Juan: Unknown.....	101	2.9	.7	42.8	22.3	15.2	1.3	.08	3.9	2.7	2.2	.1	6.0	2,120	2,160	2,500	0.36
Socorro: Carthage.....	102	14.6	.8	56.7	21.0	3.6	1.1	.02	14.0	.8	.2	.9	1.6	2,300	2,380	2,520	0.25
NORTH DAKOTA																	
Bowman: Unknown.....	103	16.9	1.5	40.4	10.6	4.1	0.9	0.04	14.7	5.4	2.5	0.2	20.3	2,130	2,180	2,260	0.65
Burke: Unknown.....	104	12.6	1.0	31.2	16.8	6.0	.9	.04	14.5	3.3	7.3	.2	19.2	2,020	2,080	2,130	0.65
Mercer:																	
Zap.....	105	12.1	1.1	23.8	10.5	10.1	.6	.27	16.6	5.1	8.2	.6	23.5	1,900	1,990	2,060	1.16
Unknown.....	106	9.3	1.0	15.4	8.0	9.2	.6	.42	23.3	6.7	7.1	.1	27.4	2,470	2,520	2,570	1.92
Ward:																	
Coteau.....	107	7.5	.5	15.0	13.0	6.1	.7	.37	36.0	10.8	.9	.3	16.6	2,430	2,470	2,520	1.89
Do.....	108	12.4	.8	31.9	13.5	5.6	.7	.13	21.4	7.0	.5	.6	16.8	2,130	2,180	2,280	0.88
PENNSYLVANIA																	
Allegheny: Pittsburgh.....	145	7.9	2.0	49.2	24.8	20.3	1.0	0.14	1.8	0.5	0.2	3.6	1.3	2,410	2,520	2,620	0.35
Armstrong:																	
Upper Freeport.....	146	10.0	1.7	50.5	27.4	16.8	1.1	.32	1.8	.9	.2	2.5	1.0	2,570	2,620	2,780	0.28
Do.....	147	10.5	2.1	47.4	26.4	19.9	.8	.52	1.8	.7	.2	2.6	1.0	2,300	2,570	2,690	0.34
Beaver:																	
Lower Kittanning.....	148	6.7	1.4	42.3	32.7	15.4	.9	1.2	2.0	.3	.2	1.2	1.6	2,620	2,780	2,910+	0.25
Upper Freeport.....	149	7.8	2.9	35.9	22.2	38.5	.9	.38	1.8	.3	.2	1.0	1.2	2,020	2,110	2,440	0.71
Bedford: Lower Kittanning....	150	10.2	.7	57.7	32.1	5.1	1.7	.18	1.7	.9	.2	2.6	.2	2,910+	-	-	-
Butler:																	
Middle Kittanning.....	151	13.4	6.3	26.9	18.2	52.5	1.1	.60	1.2	.4	.2	1.0	.8	2,000	2,060	2,230	1.20
Upper Freeport.....	152	12.4	2.8	44.9	24.7	23.1	1.8	.54	2.2	.6	.3	3.4	.8	2,180	2,260	2,520	0.41
Cambria:																	
Lower Kittanning.....	153	8.7	2.3	37.4	26.3	33.3	1.1	.11	1.8	.4	.1	1.0	1.6	2,090	2,290	2,490	0.56
Upper Freeport.....	154	12.0	2.0	46.0	24.8	22.9	.7	.13	1.7	.6	.2	2.2	1.5	2,130	2,180	2,280	0.39
Do.....	155	13.2	2.0	50.9	24.9	17.2	1.1	.30	1.7	1.0	.2	2.8	1.2	2,360	2,550	2,660	0.30
Clarion:																	
Clarion.....	156	9.9	4.5	32.7	20.9	43.3	1.0	.28	1.4	.2	.1	.8	1.4	2,110	2,130	2,420	0.84
Upper Freeport and Lower Kittanning.....	157	9.4	1.0	56.5	28.3	9.5	.9	.29	1.7	.3	.2	2.6	1.0	2,730	2,810	2,910+	0.17
Clearfield:																	
Lower Freeport.....	158	9.2	3.5	36.4	21.2	38.2	.7	.20	1.7	.3	.2	1.0	1.1	2,020	2,080	2,210	0.71
Lower Kittanning.....	159	10.9	3.6	33.9	23.7	38.5	.9	.06	1.7	.3	.2	1.3	1.1	2,100	2,240	2,570	0.72
Upper Freeport.....	160	11.5	.9	53.6	28.1	11.1	1.0	.46	1.8	.7	.2	3.2	.7	2,730	2,800	2,910	0.21
Elk: Clarion.....	161	9.7	2.3	42.1	24.3	24.6	1.3	.12	1.8	.3	.2	1.0	2.0	2,120	2,260	2,560	0.41
Fayette: Pittsburgh.....	162	9.2	2.0	49.8	25.2	16.0	1.1	.24	3.3	.7	.4	1.7	1.9	2,130	2,180	2,470	0.29
Indiana:																	
Lower Freeport.....	163	11.3	2.6	43.1	26.5	25.5	1.0	.49	1.8	.4	.2	2.1	.9	2,100	2,180	2,290	0.43
Do.....	164	8.7	1.3	49.4	31.6	11.8	1.2	.16	1.8	.8	.2	2.0	1.2	2,870	2,910	2,910+	0.20
Lower Kittanning.....	165	8.9	1.3	49.3	30.7	11.9	.9	.18	1.7	.5	.2	1.8	1.6	2,360	2,420	2,470	0.20
Upper Freeport.....	166	8.8	2.0	43.4	31.2	21.6	1.2	.29	2.1	.4	.1	1.2	1.1	2,500	2,560	2,670	0.34
Do.....	167	8.2	1.7	42.0	29.4	20.7	.9	1.1	1.9	.3	.3	1.9	1.9	2,220	2,500	2,620	0.35
Jefferson: Lower Kittanning..	168	7.6	1.1	47.5	30.8	9.3	1.6	2.9	3.6	.4	.1	1.1	1.5	2,680	2,730	2,780	0.18
Lawrence:																	
Brookville.....	169	10.3	2.4	43.4	25.6	24.2	1.6	1.2	1.9	.3	.2	1.1	.2	2,080	2,260	2,570	0.39
Lower Kittanning.....	170	11.2	3.1	33.7	18.5	42.7	1.1	.94	1.8	.3	.2	1.1	.3	1,950	2,020	2,330	0.86
Mercer:																	
Brookville.....	171	5.7	1.2	34.0	28.7	25.3	1.4	.60	5.3	.7	.4	1.2	2.7	2,250	2,340	2,560	0.51
Do.....	172	8.4	1.1	34.2	24.0	23.6	.7	.33	9.9	.7	.2	1.4	3.6	2,250	2,310	2,470	0.61
Somerset: Lower Kittanning....	173	8.0	2.3	35.1	28.7	31.4	1.0	.11	1.8	.3	.2	.6	2.1	2,180	2,420	2,550	0.53
Washington: Pittsburgh.....	174	9.8	1.1	47.6	25.8	9.6	1.1	.23	9.1	1.4	.5	1.5	3.0	-	-	-	-
Westmoreland: Pittsburgh.....	175	8.1	1.0	54.0	29.3	7.8	1.3	.14	2.7	.9	.4	1.9	1.4	2,680	2,730	2,860	0.16

TABLE 5 (continued)

County and bed	Sample No.	Percent of moisture-free coal		Analysis of ash, percent											Fusibility of ash			Base/acid ^a ratio
															Initial deformation temperature, ° F	Softening temperature, ° F	Fluid temperature, ° F	
		Ash	Sulfur	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	TiO ₂	P ₂ O ₅	CaO	MgO	Na ₂ O	K ₂ O	SO ₃					
TENNESSEE																		
Anderson: Dean.....	176	16.5	3.8	45.4	25.2	19.9	1.0	0.36	1.7	1.6	0.5	2.9	1.6	2,170	2,280	2,460	0.38	
Campbell: Dean.....	177	13.9	3.5	44.3	23.7	19.5	1.7	.73	1.8	.7	.2	2.0	2.1	2,080	2,180	2,470	0.35	
Claiborne:																		
Jellico.....	178	4.8	.9	49.4	32.7	9.5	1.7	.57	1.8	.7	.5	2.0	1.5	2,910+	-	-	-	
Do.....	179	5.2	.8	46.3	29.7	11.6	1.4	.75	1.8	1.5	.5	2.4	2.1	2,730	2,780	2,840	0.23	
Mason.....	180	10.7	1.8	46.4	27.4	17.2	.9	.13	1.7	1.5	.3	4.7	.8	2,210	2,410	2,680	0.34	
Grundy:																		
Sewanee.....	181	9.6	.9	56.5	25.8	7.3	1.0	1.1	1.7	1.5	.2	3.1	1.1	2,630	2,730	2,910+	0.17	
Upper Sewanee.....	182	9.7	.9	54.3	26.7	7.1	1.2	1.6	2.1	1.5	.2	3.0	1.1	2,610	2,670	2,730	0.17	
Marion: Sewanee.....	183	10.0	.6	55.0	25.9	6.1	1.0	1.6	2.8	1.5	.2	2.7	1.8	2,680	2,780	2,870	0.16	
Morgan: Glen Mary.....	184	6.1	2.0	44.3	28.8	20.2	1.3	.41	1.8	1.2	.2	2.9	1.2	2,130	2,230	2,420	0.35	
Scott:																		
Glen Mary.....	185	9.6	3.9	33.6	18.6	41.6	1.0	.14	2.3	.9	.4	1.0	3.0	2,020	2,080	2,140	0.87	
Stearns No. 2.....	186	17.2	4.1	43.8	25.0	23.3	1.1	.29	1.7	1.1	.3	2.1	1.8	2,020	2,080	2,290	0.41	
Sequatchie: Sewanee.....	187	11.8	1.0	53.1	26.3	7.6	1.0	1.8	1.7	1.3	.2	3.3	1.0	2,740	2,790	2,900	0.18	
UTAH																		
Carbon:																		
Castlegate D.....	188	8.1	0.4	50.5	10.3	4.9	0.9	0.62	17.2	7.6	0.4	0.4	6.6	2,110	2,260	2,390	0.50	
Do.....	189	9.6	.5	48.7	15.1	4.9	1.0	.62	13.3	6.0	.5	.6	8.3	2,190	2,260	2,360	0.39	
Rock Canyon.....	190	8.0	2.2	51.1	19.8	19.3	.8	1.4	3.5	.3	.5	.7	1.8	2,130	2,230	2,490	0.34	
Unknown.....	191	5.7	.6	55.7	15.1	6.6	.9	1.2	12.0	.6	.4	.3	4.3	2,180	2,310	2,440	0.28	
Do.....	192	7.0	.4	54.3	12.3	5.7	.9	.23	11.0	4.1	.9	1.4	8.6	2,220	2,260	2,570	0.34	
Emery:																		
Ferron "A".....	193	6.3	.5	46.7	19.2	8.0	1.3	.80	10.9	4.5	1.5	.2	6.8	2,140	2,220	2,380	0.37	
Ferron J.....	194	8.2	1.4	39.4	15.5	9.6	1.2	.20	17.0	4.5	3.1	.1	8.1	2,070	2,120	2,210	0.61	
Unknown.....	195	9.6	.7	58.1	20.3	3.7	1.2	.55	5.7	.8	4.2	1.1	2.8	2,360	2,420	2,570	0.49	
Do.....	196	7.2	.5	63.2	13.8	4.3	.8	.10	5.9	1.0	4.3	1.1	4.9	2,180	2,310	2,530	0.21	
Sevier: Hiewatha.....	197	6.9	.4	46.4	9.1	7.0	.6	.03	21.9	3.6	1.0	.1	7.5	2,080	2,110	2,150	0.60	

^aBase/Acid Ratio = $\frac{\text{Fe}_2\text{O}_3 + \text{CaO} + \text{MgO} + \text{K}_2\text{O} + \text{Na}_2\text{O}}{\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{TiO}_2}$ (from Reference 14).

POTENTIAL IMPACT OF COAL CHEMISTRY ON FLY ASH BEHAVIOR

The manner in which the chemical composition and, in particular, the ratios of certain chemical species can affect both the combustion characteristics of a coal as well as the collectability of its fly ash are indicated in Table 6. The summarized excerpts of several ASME tests¹⁴ intended originally to establish the slagging or fouling potential for coal fly ashes (Table 6) also suggest useful guidelines as to how the physical and chemical properties of the ash exiting from the boiler proper may behave in a filter system. Typical values for several characteristic ratios along with ash softening temperatures, coal sources, and mineral assays are shown in Tables 5, 7 and 8 for various U.S. coals.

Exclusive of those ash properties relating to the combustion and heat transfer aspects of the boiler operation, other factors can be identified that may affect the ultimate filterability of the ash. These are melting or fusion temperatures and the ash viscosity in the molten state, the capacity to react with gases and/or to absorb moisture, and the ability to retain or lose electrical charge as a function of fly ash resistance properties. Additionally, the sulfur-iron balance for the coal indicates the extent to which the total sulfur content can be removed by pyrite separation during coal upgrading. One may infer from a low ratio that the coal sulfur is mainly organically bound and thus more likely to appear in the flue gas where it can adsorb on, or react with, the alkaline constituents of the ash. In the following section, the several chemical and physical factors identified with typical U.S. coals are discussed in relation to their impact upon fly ash filterability.

Fusion Properties, Hygroscopicity, Chemical Reactivity, and Electrical Charge

At the outset of this study, it was recognized that a rigorous screening process would be required to reduce the number of variables to an acceptable level, particularly so in the case of certain chemical constituents and/or their combinations. Since, it appeared that the fusion properties of the mineral components of the coals were frequently associated with various ratios and combinations of selected elements found in the ash, a preliminary effort was made to identify specific coal assays that offered the strongest correlations with fusion temperature. It was assumed that the ultimate size of molten ash particles should relate, in part, to the fluidity and hence the viscosity and surface tension of the molten ash and the turbulence and shearing action generated during the combustion process. Thus, those chemical interactions known to decrease the viscosity of the molten ash particles were expected to reduce to some degree the size of the fly ash particles approaching the control device. On the other hand, the same turbulent effects shattering the droplets will also increase the agglomeration rate. Given the tacky or sticky surfaces of the ash particles, irreversible collisions may cause an appreciable particle growth that could conceivably offset the shattering phenomena. Thus, as reported by Horney,⁶ the ultimate size parameters may be difficult to predict based upon the chemical constituents of the ash. From a qualitative perspective, a reduced size should increase the K_2 value for the ash and hence make it more difficult to filter.

TABLE 6. COAL FOULING AND SLAGGING PARAMETERS THAT MAY AFFECT FLY ASH FILTERABILITY

ASME tests ^a	Properties measured and/or effect on boiler	Expected effect on fly ash size properties	Reported effects on size properties
1. Ash Fusion Temperatures	Deformation to fluid temperatures, ash plasticity and fluidity.	No size changes at high fusion temperatures. Possible decrease in size due to shattering of molten particles as fusion temperature decreases but with concurrent particle growth, due to agglomeration of colliding, tacky, particles.	Size properties exhibit minimum value at medium fusion temperature with maximum ¹ shown at low and high fusion temperatures. ¹⁵
2. Silica Ratio $\frac{SiO_2}{SiO_2 + Fe_2O_3 + CaO + MgO}$	Slag viscosity increases with silica ratio.	Reduced droplet shattering at increased viscosity but with probability of particle growth by agglomeration.	See (1) above. ^b
3. Silica-to-Alumina Ratio $\frac{SiO_2}{Al_2O_3}$	High alumina acts as flux with low base slag.	Increased fluidity causes droplet shatter but also growth by agglomeration.	See (1) above. ^b
4. Base-to-Acid Ratio (B/A) $\frac{Fe_2O_3 + CaO + MgO + K_2O + Na_2O}{SiO_2 + Al_2O_3 + TiO_2}$	Melting point lowest with 50:50 ratio with increasing melting point at very low B/A or very high B/A.	Decreased droplet size at reduced melting point but with parallel growth due to agglomeration. Note Fe ₂ O ₃ in ash roughly proportional to B/A ratio.	Fly ash exhibits minimum size at medium Fe ₂ O ₃ contents. Higher values reported for low and high Fe ₂ O ₃ values. ¹⁴
5. Dolomite Percentage (D.P.) $100 \times \frac{Fe_2O_3 + CaO + MgO + K_2O + Na_2O}{Fe_2O_3 + CaO + MgO + K_2O + Na_2O}$	High Dolomite Percentage with a fixed percent base indicates higher melting point and viscosity.	Minimal change in parent particle size and shape at high melting points, but finer particles due to easy pulverizing of dolomites.	Size properties vary inversely with dolomite content, agglomeration minimal. ¹⁴
6. Sulfur-Iron Balance Total Fe ₂ O ₃ in ash $\frac{Fe_2O_3 \text{ equivalent of 50 percent of sulfur as FeS}_2}{\text{Total Fe}_2\text{O}_3 \text{ in ash}}$	Analysis indicates fraction of sulfur potentially separable as pyrites at mine head.	Fly ash acidity and capacity to absorb moisture increases with high sulfur and low pyrites, possible particle growth. Increased electrical conductivity and charge leak off-possibly denser cake with high (aerodynamic) resistance.	
7. Sodium Content of Coal Ash	Contributes to corrosion in boiler and fouling.	Increased ash conductivity implied - possible asset with ESP. May lead to moisture absorption and particle growth. Filter plugging if condensation occurs.	Size increases with increasing sodium content. ⁸
8. Total Alkali Content (T.A.) ($\frac{1}{2} Na_2O + 0.6589 \times \frac{1}{2} K_2O$) $\times$ % Ash/100 Water Soluble Content Na and K content by boiling and reflux in water.	Normalized Na ₂ O + Na ₂ O equivalent of K ₂ O affects furnace corrosion and fouling characteristics. Indicates readily vaporizable forms of sodium that may foul and corrode tubes.	See (7) above. Suggests conducting and potentially hygroscopic particles. Filter plugging if condensation occurs.	

^a ASME Tests 1 through 5 excerpted from Reference 14, Test 6 excerpted from Reference 15.

^b Effects assumed to be the same as described for fusion temperature variations in Reference 16.

TABLE 7. SOFTENING TEMPERATURES, ASH CONSTITUENTS AND CHARACTERIZING RATIOS FOR SEVERAL U.S. COALS

Coal source	Coal region	Softening temperature °F	Coal ash analysis, percent												Total percent	Base/acid ratio*	Silica/alumina ratio	Alumina/silica ratio	Dolomite ratio
			SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	TiO ₂	CaO	MgO	Na ₂ O K ₂ O	SO ₃									
Montana Subbituminous	VI	2069	30.7	19.6	18.9	1.1	11.3	3.7	2.4	12.2				99.9	0.71	1.57	0.64	0.50	
Illinois Bituminous	IV	2320	46.2	22.9	7.7	1.0	10.1	1.6	1.5	8.9				99.9	0.30	2.01	0.49	1.56	
Pennsylvania Bituminous	I	2500	49.7	26.8	11.4	1.2	4.2	0.8	2.9	2.5				99.5	0.25	1.85	0.54	0.26	
West Virginia Bituminous	II	2730	51.0	30.9	10.7	1.9	2.1	0.9	1.4	0.6				99.5	0.18	1.65	0.61	0.20	
Kentucky Bituminous	II	+2900	58.5	30.6	4.2	1.8	2.0	0.4	1.6	0.9				100.0	0.09	1.91	0.32	0.29	

NOTE: Softening Temperature and Ash Analysis excerpted from Reference 16.

$$\text{Base/Acid Ratio} = \frac{\text{Fe}_2\text{O}_3 + \text{CaO} + \text{MgO} + \text{Na}_2\text{O} + \text{K}_2\text{O}}{\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{TiO}_2}$$

$$\text{Silica/Alumina Ratio} = \frac{\text{SiO}_2}{\text{Al}_2\text{O}_3}$$

$$\text{Dolomite Ratio} = \frac{\text{Fe}_2\text{O}_3 + \text{CaO} + \text{MgO} + \text{K}_2\text{O} + \text{Na}_2\text{O}}{\text{CaO} + \text{MgO}}$$

TABLE 8. CHEMICAL COMPOSITION OF TYPICAL COAL ASHES^a

	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	SO ₃	Total ^b oxides	Percent oxides		Base/Acid ratio ^c	SiO ₂ /Al ₂ O ₃ ratio
										Acidic	Basic		
Alabama, Tuscaloosa County	48.2	28.4	15.1	1.8	0.8	0.3	1.2	2.4	98.2	79.8	18.4	0.23 (1)	1.7
Colorado, Moffat County	34.8	22.7	6.0	12.8	2.0	3.0	0.3	15.1	96.7	72.0	24.2	0.34	1.53
Illinois, Kankakee County	36.0	20.5	35.4	1.8	0.8	0.6	1.8	1.2	98.1	57.7	40.4	0.70	1.75
Stark County	42.1	20.1	22.8	6.6	1.1	0.5	1.9	2.0	97.1	64.2	32.0	0.51 (2)	2.09
Schuyler County	48.0	14.7	18.7	10.4	0.6	0.2	1.8	2.1	96.5	64.8	31.7	0.49 (2)	3.26
Kentucky, Pike County	52.0	34.5	6.4	1.9	0.6	0.5	3.3	0.8	99.7	87.0	12.7	0.15 (1)	1.51
Bell County	46.9	28.4	12.0	2.7	2.0	0.2	2.0	4.5	98.7	79.8	18.9	0.22 (1)	1.66
Ohio County	49.3	19.4	27.4	1.8	0.7	0.2	1.9	0.2	100.0	69.0	31.0	0.45 (2)	2.54
North Dakota, Mercer County	23.8	10.5	10.1	16.6	5.1	8.2	0.6	23.5	98.5	40.6	57.9	0.78	2.27
Ward County	15.0	13.0	6.1	36.0	10.8	0.9	0.3	16.6	98.7	44.6	54.1	1.22	1.15
Ohio, Belmont County	42.4	19.6	27.5	4.8	1.2	0.2	1.6	2.0	99.3	64.0	35.3	0.55 (2)	2.16
Jefferson County	50.4	23.2	12.0	1.9	0.5	0.1	1.0	0.4	99.4	74.0	25.4	0.34 (2)	2.17
Noble County	36.7	19.9	37.8	1.8	0.6	0.2	1.4	0.7	99.1	67.1	32.2	0.48 (2)	1.84
Pennsylvania, Bedford County	57.7	32.1	5.1	1.7	0.9	0.2	2.6	0.2	100.5	90.0	10.5	0.12 (3)	1.80
Allegheny County	49.2	23.2	20.3	1.8	0.5	0.2	3.6	1.3	101.7	75.3	26.4	0.35 (2)	1.98
Butler County	26.9	18.2	52.5	1.2	0.4	0.2	1.0	0.8	101.2	45.9	55.3	1.20 (2)	1.48
West Virginia, Barbour County	52.5	35.6	6.1	1.8	0.6	0.2	1.9	0.9	99.6	89.0	10.6	0.12 (3)	1.47
Fayette County	48.5	30.1	13.6	1.8	0.8	0.7	2.6	1.3	99.4	79.7	19.8	0.25 (1)	1.61
Kanawha County	37.9	23.8	31.4	2.0	0.5	0.5	0.5	2.9	99.5	64.5	34.9	0.54 (2)	1.60

^aOxide composition statistics from Reference 15, Table 6-1.^bDifference from 100 percent due to round-off errors and unreported trace element oxides.^cExpected seam similarities based upon location and geology indicated by index numbers in parentheses.

Concurrently, diminished size should also lead to more particle-fabric contacts in the interface region, thus making it more difficult to dislodge the dust cake during routine cleaning operations.

Additional factors expected to influence the actual filtration properties of the ash were the reactivity of the ash with acid gases, mainly sulfur oxides, and the hygroscopicity of the freshly formed ash particles or their reaction products, the latter occurring principally as sulfates, sulfites, and bisulfites. In the first instance, moisture absorption under near dew point conditions will cause fly ash deposits to become sticky and hence difficult to dislodge from fabrics. Furthermore, actual decreases in dust cake porosity due to moisture absorption and actual liquification within the capillary structure of the cake will effectively plug the fabric, thus diminishing its gas handling capacity and ultimately causing filter failure.

Although the concentrations of soluble and readily ionizable salts coupled with gas temperatures safely above the dew point may minimize dust plugging, secondary effects may take place because of electrical charging phenomena. The presence of conducting salts in the fly ash should enable more rapid dissipation of charge from dust deposits. With no accumulation of charges (unipolar) induced by thermal dissociation or contact electrification in the combustion zone, particle repulsion effects within the close confines of the dust layer may be reduced. The result may be an increase in pressure loss (higher K_2) due to decreased cake porosity. On the other hand, should charge loss from the fabric be inhibited by its intrinsically low conduction (high resistivity), image force effects might increase the level of adhesion between the dust layer and the underlying fabric. Thus, although resistance to filtration may be reduced, the dust may be more difficult to dislodge from the fabric.

Base/Acid Ratio

Listings of the principal elements found in several U.S. coal ashes expressed as their percent oxide equivalent are presented in Tables 5, 7, and 8 along with their characterizing Base/Acid (B/A) ratios. As indicated previously in Tables 5 to 7, very high or very low B/A ratios are usually associated with high melting point ashes. Conversely, minimal melting points with a rapid transition from the solid to the liquid phase are observed with a 50:50 mix ($B/A = 1/1$). Observed fusion temperatures relating to the fraction basicity or acidity are shown in Figure 5. The idealized phase diagram, Figure 6, suggests that the transition from the solid to liquid state is most rapid for very high or low B/A ratios.

An inspection of B/A ratios for several coals, Tables 5, 7 and 8, indicates that geographical and geological factors are important in determining this attribute. Those coals identified by the same index numbers, Table 8, come from areas where a) geological factors relating to the history of seam composition are similar or b) where the coals are from contiguous seams or coal fields that overlap State and County boundaries. According to the data presented in Figure 5 and Table 8, the melting points for coals mined in areas designated by index numbers 1, 2, and 3, respectively, are 2300, 2100, and 2650°F. One infers, therefore, that very low or very high B/A

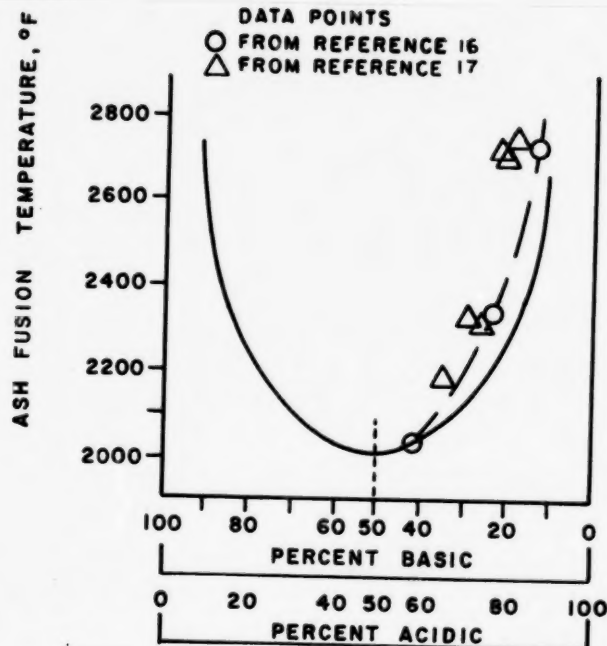


Figure 5. Acidic content of ash vs. ash fusion temperature.
(Courtesy Babcock and Wilcox Company)

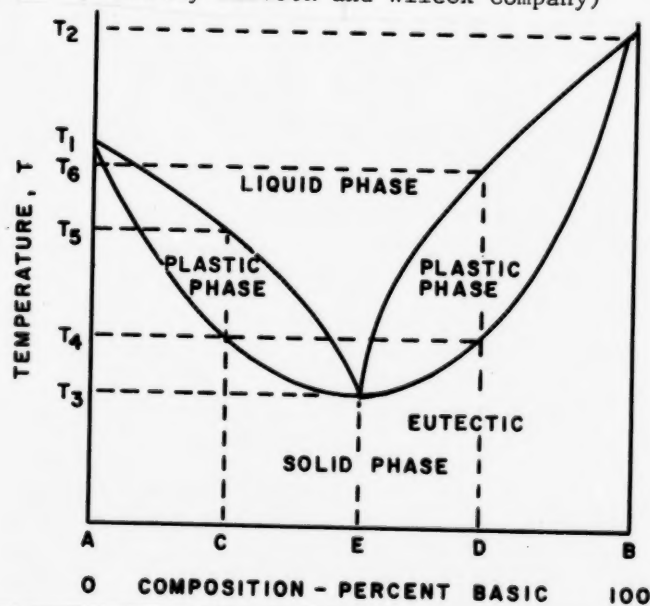


Figure 6. Idealized phase diagram showing physical state and temperature of ash as a function of base content.

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ratios are indicative of high melting temperatures and hence a potential contributor to increased fly ash size. With reference to the sandstone and shale overburdens described in Table 3, the lower B/A ratio for sandstone (~ 0.12 vs. 0.23) is consistent with its higher melting point. The fact that fusion data from other sources¹⁶ shown by the encircled points on Figure 5 also display the same trends lends credibility to this parameter.

Figure 7 shows that the iron oxide content of the ash, which is related directly to the B/A ratio, also differs characteristically depending upon the location of the coal seam. Conversely, the silica to alumina ratio bears no apparent relationship to seam location, thus suggesting it to be a poor indicator of fly ash fusion properties. Although the combustion engineer is concerned mainly with the potential slagging and fouling properties of coals from the perspectives of combustion rate, heat transfer efficiency, and finally ash removal and storage, the same fusion properties that affect ash fluidity, viscosity, or non-melting characteristics are believed to influence the shape and size properties of the aerosolized fly ash. Under the latter circumstances, one may then infer that the filterability of a fly ash as defined by its specific resistance coefficient, K_2 , and the ease with which the fly ash can be dislodged from a fabric during repetitive cleanings, should depend to some extent on the fusion or melting properties of the parent coal.

In the following paragraphs, we have presented a more detailed analysis of the relationship between B/A ratios and the deformation, softening, and fluid temperatures for several U.S. coals. Although deformation temperature is not expected to alter the mass of a particle (no disintegration), it can influence particle shape by smoothing sharp edges or rough surfaces while contributing to the "rounding out" of an ash particle. It is presumed that any process tending to create a smoother and more symmetrical particle will affect the bulk density, or porosity of any deposited dust layers. Given a fixed approach velocity, it is anticipated that the elimination of any constraining edges or surface roughness will cause the particle layer to assume a denser and therefore a less porous configuration. Additionally, once softening occurs, particle surfaces become tacky such that particle collisions engendered by gas stream turbulence can lead to agglomerate formation.^{18,19} Although such particles are frequently observed among fly ash populations, e.g. many small, highly diffusive particles attached to the surface of large, $\sim 10 \mu\text{m}$, particles (the latter being relatively immobile), it is difficult to determine whether the overall fly ash size parameters are significantly altered.

The coal analyses and fusibility properties forming the basis for B/A and other parameter assessments have been excerpted from a U.S. Bureau of Mines document R.I.7240 prepared by Abernethy et al.¹³ The sampling of coals listed in Table 5 embrace the six major coal producing regions described earlier (Figure 1 and Table 1). Insofar as volatiles, sulfur, ash, and moisture contents are concerned, there are few distinguishing features among coals from Region I through III. It should be noted, however, that the B/A ratios for the same regions may show significant differences, Tables 8 and Figure 7.

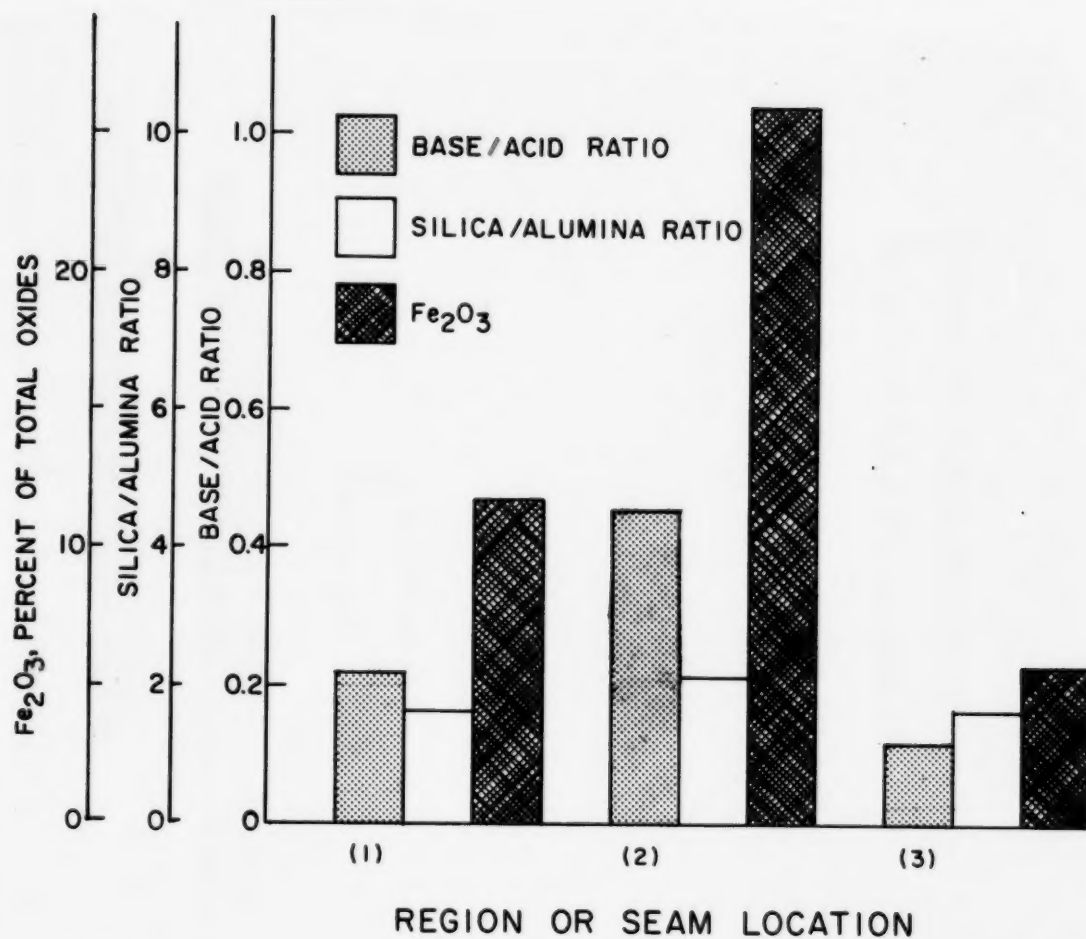


Figure 7. Characterizing ratios versus location of coal seam. Refer to Table 8.

To facilitate graphing, B/A ratios greater than unity have been converted to their reciprocal values because fusion temperatures display minimum values when the B/A ratio is unity (see Figure 5). A rough estimate of how strongly ash fusion properties correlates with B/A ratios is indicated by the simple linear regression analyses of Table 5 data. The "r" value of 0.81 for a sampling of 93 data point pairs signifies that there is less than a 0.1 percent chance that no correlation exists. It is emphasized, however, that one cannot automatically assume that a strong correlation between B/A ratios and ash fusion properties means that fly ash size properties (and derived parameters) will correlate equally well. Subsequent attempts to develop viable relationships between K_2 and B/A ratios are discussed in a later section of this report.

SiO₂/Al₂O₃ Ratio

Because of the varied mineral constituents found in coals and the potential for a multiplicity of chemical reactions, the SiO₂/Al₂O₃ ratio has also been proposed for predicting melting point and viscosity characteristics.¹⁴ A low value for the silica to alumina ratio has been associated with a reduced slag melting point based on the fluxing action of the alumina when the base or alkaline metal content of the fly ash is low. The more rapid transition to the fluid state may lead to a reduced size for the ash fusion products due to droplet shattering, although the surface stickiness may also cause agglomerate formation as discussed earlier for a B/A ratio of 1/1. A high value for the ratio may also indicate that the extraneous silica in the coal is associated with sandstone formations containing relatively hard, quartzitic materials. Consequently, the mineral fraction of the coal pulverizer product might be expected to be coarser. According to Figure 6 and Table 7, however, SiO₂/Al₂O₃ ratios show relatively small differences from seam to seam. One may infer, therefore, that for the coals in question, the fusion properties are at best only weakly related to the silica/alumina ratio. Consequently, further study of this parameter was discontinued in the present program.

Dolomite Ratio or Dolomite Percentage

Limited information for the Dolomite Ratio (DR), Table 3, indicate that sandstone, whose melting point exceeds that for slate, shale and claystone also has the larger dolomite ratio; i.e., 0.68 versus 0.33. Although the above findings are consistent with Table 6 projections, a subsequent analysis of dolomite percentages for several western and eastern coals, Table 7 and Figure 6, belied any useful correlations between fluid temperature and dolomite percentages. According to the literature,¹⁴ DR ratios are best applied to western coals that are generally more basic, >40 percent, and where the base/acid ratios are similar. However, the point scatter indicated on Figure 8, which involves a broad range of DR ratios, was not improved even when comparisons were made at the same levels of alkalinity. Therefore, it was decided to discontinue further investigations of the dolomite ratio.

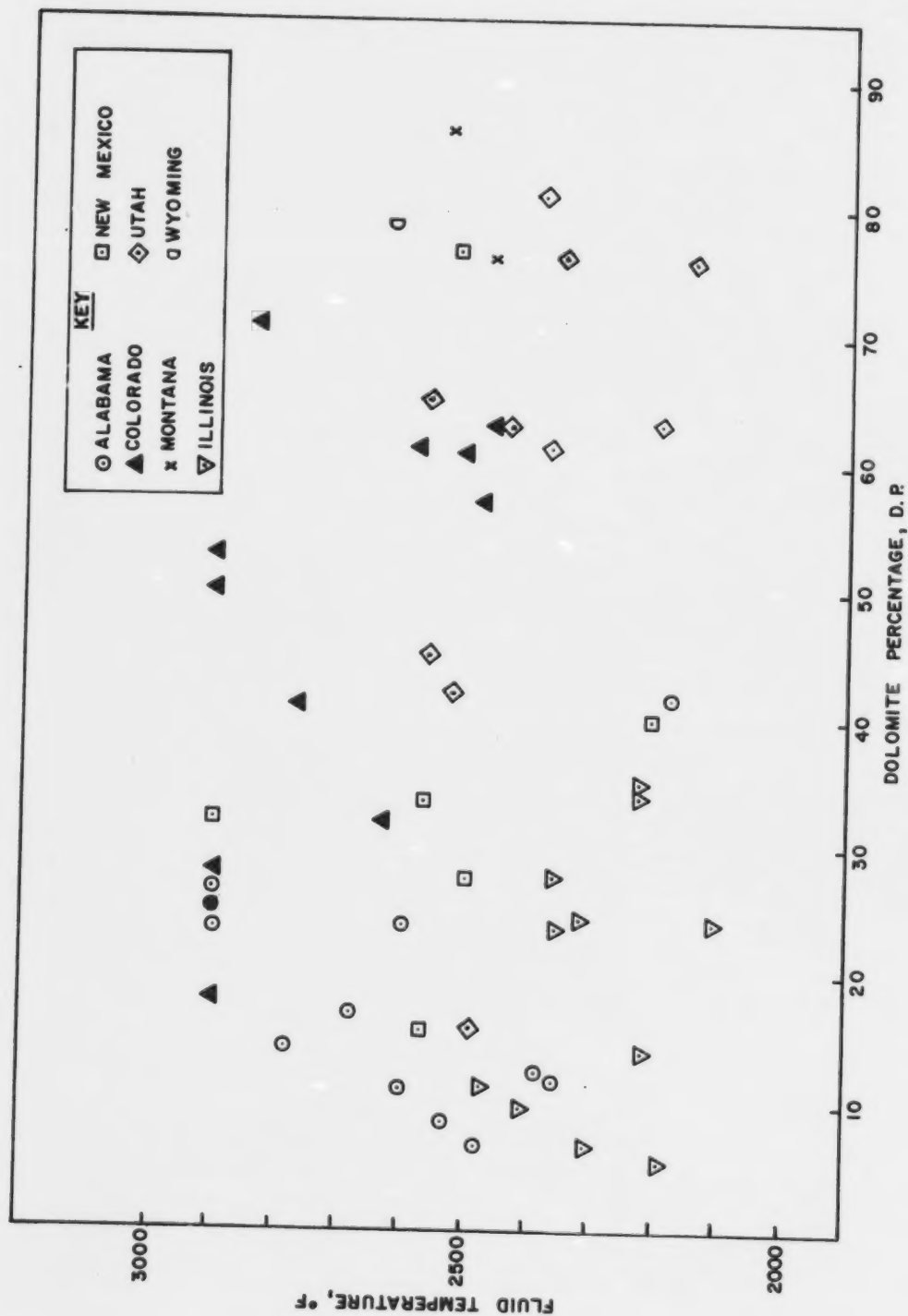


Figure 8. Fluid temperatures vs. dolomite percentages for various eastern and western coal ashes computed from data appearing in Table 5.13

Sulfur-Iron Balance

According to the literature, it is highly probable that a sulfur-bearing coal with a high iron content also contains a large fraction of pyritic iron.¹⁵ Given the same sulfur content but with a low iron content, one usually makes the opposite assumption; i.e., the sulfur source is the degraded flora from which the coal was formed. The practical significance of the sulfur source is that sulfur present in the pyritic form can be partially removed by gravity separation procedures. The less readily separated organically bound sulfur, however, will be converted upon combustion to a mix of soluble sulfur compounds such as alkali metal sulfites, bisulfites, and sulfates which, when collected on a filter, can contribute to a potential plugging problem if gas stream temperatures fall below the dew point.

In Table 9, sulfur-iron balances are shown for several U.S. coals.¹⁵ The ratios of the total measured iron oxide quantity present in each coal to the iron oxide level equivalent to one half the measured coal sulfur content is given in the last column. The 50 percent equivalency is based on the assumption that the sulfur content of an average coal is equally distributed between an organic and a pyritic fraction. Reference to Figure 9 indicates that the 50:50 assumption is reasonable for total sulfur contents below 2.5 percent. However, it appears that a larger fraction of the sulfur may arise from biological origins in those coals with very high iron content. Because data are usually readily available for coal sulfur contents in contrast to those for the other chemical constituents, it was decided to investigate additional correlations between coal ash fusion characteristics and particle size and/or K_2 values. The latter analyses are presented in a subsequent section.

Ash Softening Point

Various characterizing ratios have been discussed previously that relate to the overall fusion properties of many fly ashes. Two additional correlations were made for Alabama coals in which total ash and total sulfur contents were examined as potential melting property indicators. It was assumed that if sulfur content were related to coal iron content, as shown in Figure 9, the fraction of iron in the pyrite form would be less for the higher sulfur contents. According to Nielson,⁴ improved ash fluxing and lower fusion temperatures might be anticipated with less iron in the pyrite form. However, the data point array shown in Figure 10 does not substantiate this fact.

On the premise that an increase in coal mineral content might conceivably result in a proportionate reduction in heat transfer to individual mineral particles because of the brief retention times in the flame zone, it was decided to examine the effect of increasing ash content on its softening point. Although a trend toward lowered softening points is suggested for low ash coals, the data shown in Figure 11 afford no useful means to predict melting properties. An inverse correlation between K_2 values and ash content discussed later in this report, however, appears to lend some validity to the heat transfer concept. Given a choice, it is obvious that direct measurements of ash fusion properties would be preferable to any estimates derived indirectly from characterizing ratios of ash constituents,

TABLE 9. SULFUR-IRON BALANCE FOR TYPICAL U.S. COALS¹⁵

State	Ash percent	Sulfur percent	Fe ₂ O ₃ in ash percent	Fe ₂ O ₃ ^a in dry coal percent	Fe ^b in dry coal percent
Colorado	15.9	0.4	5.3	0.843	0.59
	12.3	0.6	3.3	0.406	0.28
	5.2	1.1	11.9	0.619	0.43
Illinois	6.5	2.7	35.4	2.30	1.61
	9.1	3.0	20.0	1.82	1.28
	12.7	4.5	34.8	4.42	3.10
Kentucky	8.6	0.8	4.5	0.387	0.27
	2.2	1.1	20.0	0.440	0.31
	6.8	3.3	31.3	2.13	1.49
North Dakota	7.5	0.5	6.1	0.458	0.32
	12.4	0.8	5.6	0.695	0.49
	16.9	1.5	4.1	0.692	0.49
Ohio	12.4	2.6	16.8	1.68	1.18
	10.8	4.3	27.5	2.97	2.08
	14.7	6.3	39.7	5.83	4.08
Pennsylvania	10.2	0.7	5.1	0.51	0.36
	9.9	4.5	43.3	4.29	3.61
	13.4	6.3	52.5	7.04	4.93
Utah	8.1	0.4	4.9	0.397	0.28
	9.6	0.7	3.7	0.355	0.25
	8.0	2.2	19.3	1.54	1.08
Wyoming	6.4	0.6	9.0	0.576	0.40
	14.4	1.8	10.3	1.48	1.04

^aRange, >0 <8.0.^bRange, >0 <5.0.

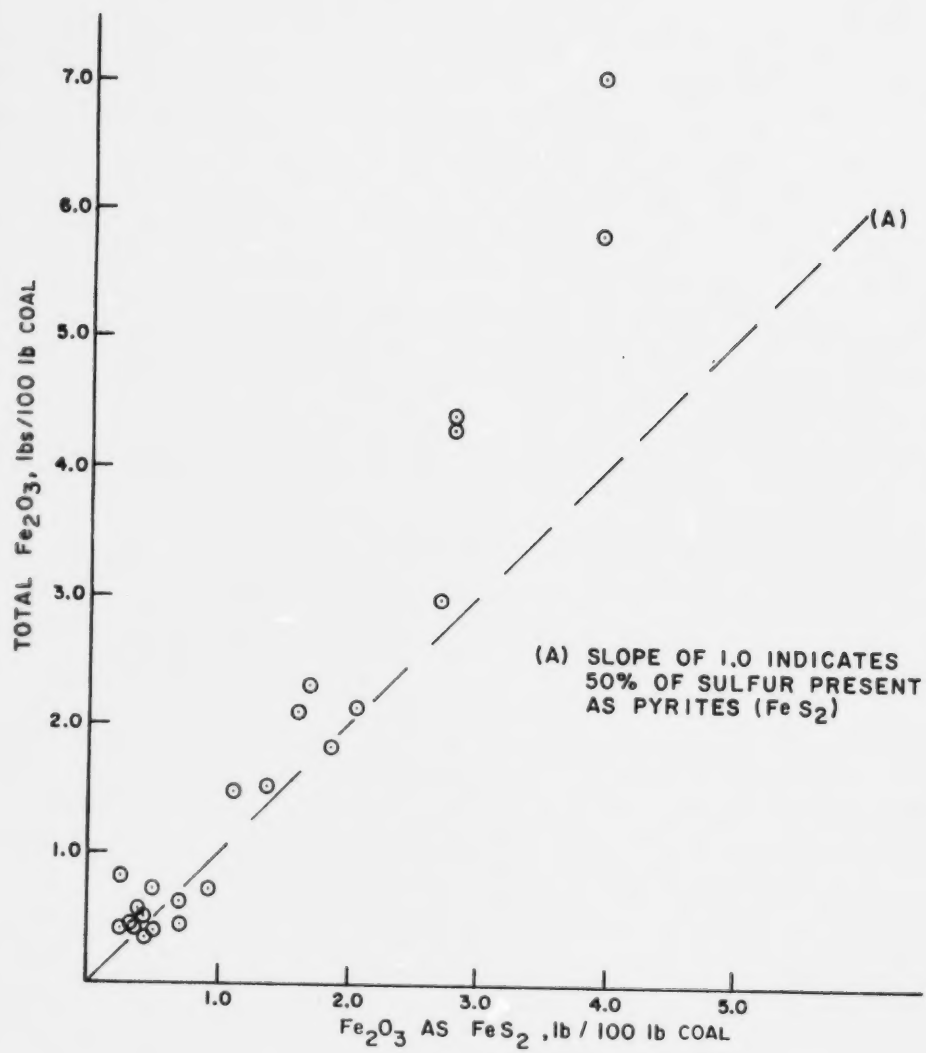


Figure 9. Total iron oxide in coal vs. iron pyrite equivalent of iron oxide.¹⁵

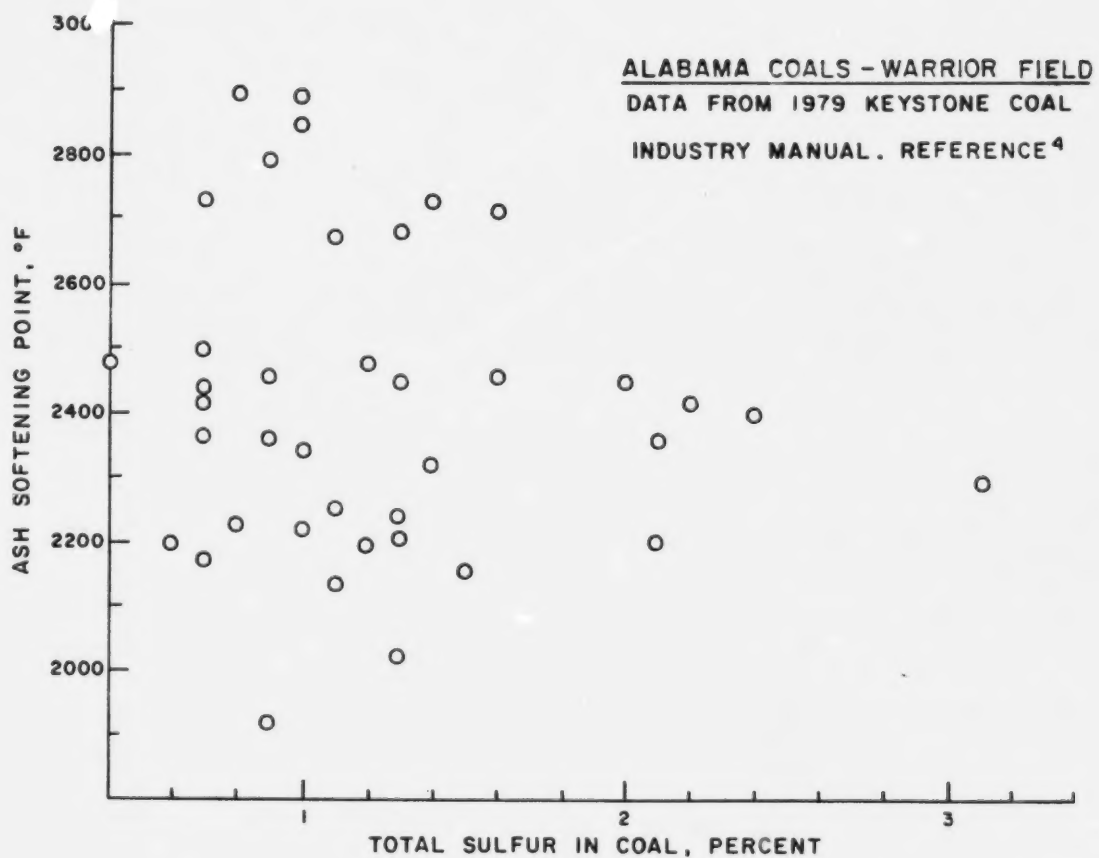


Figure 10. Effect of sulfur content of "as received coals" on ash softening point.

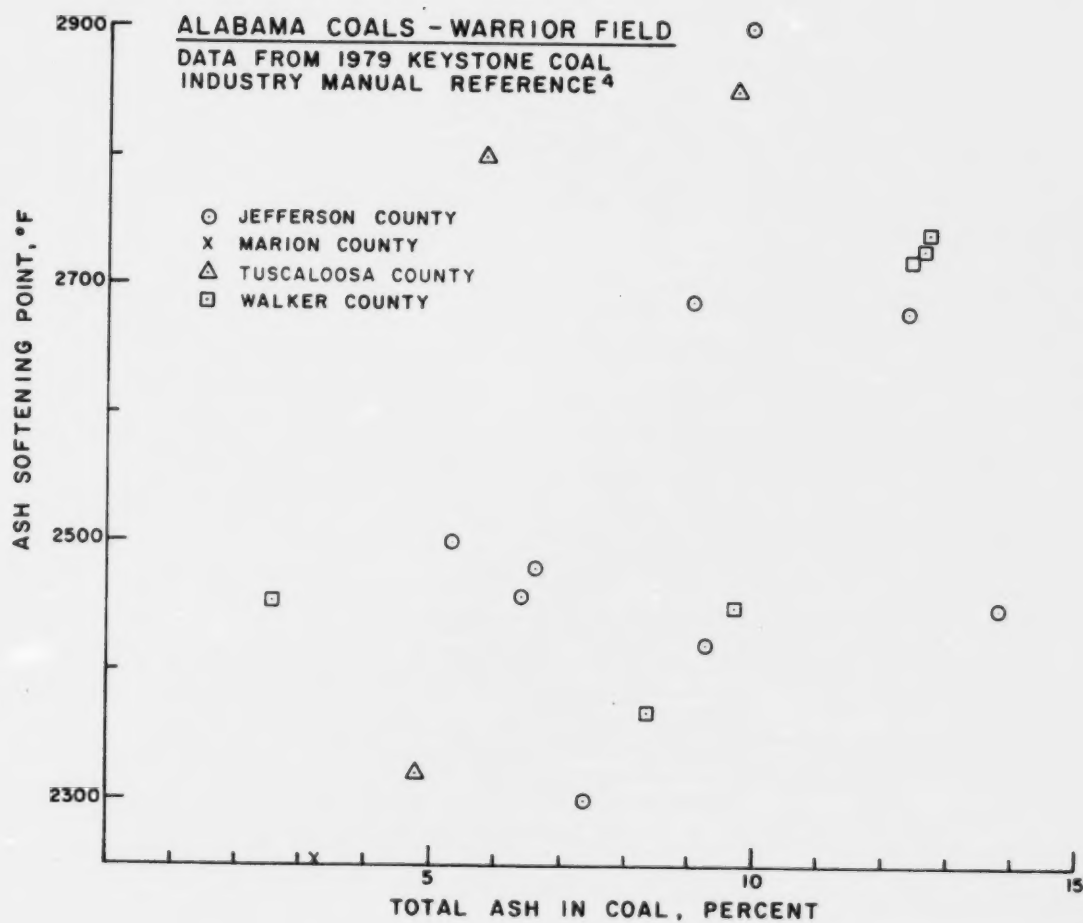


Figure 11. Effect of total ash content on ash softening point.

composition, or physical properties. Unfortunately, it appears that more data are available and/or reported for ash analyses than for the corresponding melting, softening, or fusion temperatures. In a later section, the significance of fusion properties relative to their effect on fly ash size and filtration properties will be examined critically.

SECTION 4

BASIS FOR SELECTION OF REPRESENTATIVE COALS

It has been emphasized that the selection of fly ash samples for special laboratory testing should represent not only the diversity in composition of the parent coals but also the best projections of the present and future uses of these coals in applications where fabric filters provide the particulate emission control. Despite the variability in coal assays from region to region as well as within a given region or even a typical coal seam, reference to the average values for proximate and sulfur analyses suggested that coals from Regions I through III representing the eastern U.S.A. (Figures 1 and 2) are associated with fly ashes having similar filtration properties. Thus, as a first approximation, four rather than six geographical regions were chosen to provide a representative coal sampling.

Where high sulfur contents contribute significantly to increased fly ash hygroscopicity (and a high filter pressure loss at below dew point operation) it was believed that Region IV coals might produce distinctive and possibly troublesome fly ashes. On the other hand, the low sulfur content of many western coals, Region VI, may alleviate acid dew point problems but cause increased electrical charge accumulation due to a high cake resistivity. Region V coals are characterized by high ash contents and higher than average sulfur content, Figure 2, both of which can adversely influence overall filter system performance.

On the premise that ash fusion properties could be related to ultimate fly ash size properties, the Base/Acid ratio suggested itself as a useful predictor. According to Table 5, however, no clearly defined relationships were evidenced between Base/Acid ratios and coal producing Regions insofar as Regions I through VI were concerned. Therefore, it was decided that when more than one sample was to be obtained from a specified coal region, the B/A ratios would be investigated. Consideration was also given to lignite in view of its increasing use in large western electric generating plants. Because of potential acid damage to fabrics associated with high sulfur coals, it was decided that the coal sampling should also include fly ash from at least one high, 3 to 4 percent, sulfur coal. Paired samples for at least two coals, each represented by a stoker and a pulverized firing application, were also sought in the preliminary coal selections.

Despite the many characterizing ratios discussed previously, it appeared that only the B/A ratio, with its attendant effect on ash fusion properties, offered potential as a fly ash size predictor, Figure 5. The reason for considering the effect of sulfur content was that an increase of soluble

sulfur reaction products in the form of alkali metal salts is expected to increase the moisture absorbing properties and hence the pressure loss of the filter dust deposits. Increased coal ash content, regardless of its impact on fly ash size properties, automatically increases the filter dust burden for a fixed power generation rate such that increased pressure loss and the need for more frequent cleaning is anticipated.

Based upon the factors discussed above, a tentative listing of fly ash selections was prepared, Table 10, based upon the coal source (region), chemical and/or physical composition, and method of firing. At the inception of this study, it was believed that smaller stoker-fired boilers might assume larger roles in utility application than actually determined later in this program. Hence, the number of stoker units actually proposed for study is somewhat larger than might have been selected on a megawatt basis alone. On the other hand, a very large increase in the construction of ~500 to 1000 M power stations has taken place in Region VI during the last year of this study. Despite the fact that the representativeness of the fly ash samples are very dependent on the sample availability, the actual response from several cooperating utilities led to a composition spectrum that reflected a strong swing to large western stations. Because at least two pounds of fly ash were required for testing purpose, it was requested that the dust be obtained from baghouse dust hoppers. The very high efficiencies attainable with baghouses coupled with the fact that several GCA measurements have shown that fly ash size distributions are frequently nearly the same up- and downstream of the filter fabric guarantees a representative sampling. It must be recognized that redispersal of these bulk fly ashes, even with high energy dust generators such as compressed air ejectors, rarely reduces the airborne re-suspensions to their parent particle size distributions. Although fly ash from ESP hoppers could have been used, its size properties would have been less representative because of excessive penetrations by the $\sim 1 \mu\text{m}$ size fraction. Listings of utility and industry sources who have been contacted to furnish samples of their baghouse-collected fly ash are given in Appendices A-1 and A-2. A listing of cooperating groups identified with respect to State, Coal Region and Industrial (I) or Utility (U) source is given in Table 11.

TABLE 10. TENTATIVE SPECIFICATIONS FOR FLYASH SAMPLING BASED ON COAL SOURCE, PROPERTIES, AND FIRING METHOD

Coal producing region ^a	Regional coal ^b production % of total	Total samples	Fly ash sample distribution					
			Group 1		Group 2		Group 3	
			Base/acid ratio	Firing method	Percent sulfur	Firing method	Percent ash	Firing method
I	26.2	1	Low, 0.17	Pulv.			Medium ~10%	Pulv.
II	22.5	3	Low, 0.17	Stoker Pulv.			Low ~5%	Pulv.
III	2.6	2			Medium 1.3-1.9%	Pulv.		
IV	24.6	3	High, 0.5	Stoker	High >3.0%	Pulv. Stoker		
V	4.6	1					High >15%	Pulv.
VI	19.5	4	High, 0.5	Pulv.	Low 1.0%	Pulv. Stoker	High >15%	Pulv. ^c

^aSee Figure 1 for geographical location.

^bCoals are bituminous or subbituminous unless otherwise indicated.

^cWestern lignite.

TABLE 11. COAL FLY ASH SAMPLES RECEIVED FOR LABORATORY TESTING

Boiler location State ^a	Coal source ^b		Percent of ^b regional coal production
	State	Region	
Ohio (I)	Pennsylvania	I	26.2
Pennsylvania (U)	Pennsylvania	I	
Kentucky (I)	Kentucky (East)	II	22.5
North Carolina (I)	Kentucky (East)	II	
Georgia (U)	Alabama Tennessee (South)	III	2.6
Illinois (U)	Illinois	IV	24.6
Indiana (I)	Indiana	IV	
Texas (U)	Texas	V	4.6
Colorado (U)	Colorado	VI	19.5
Colorado (U)	Colorado	VI	
Colorado (U)	Colorado	VI	
Idaho (I)	Wyoming	VI	
Nebraska (U)	Colorado	VI	
Nebraska (U)	Wyoming	VI	
Texas (U)	Wyoming	VI	
Utah (I)	Colorado	VI	
Washington (I)	Utah	VI	

^a(I) refers to industrial user. (U) refers to electric utility plant.

^bCoal regions and production statistics listed in Table 1.

SECTION 5

TEST MATERIALS, EQUIPMENT, AND PROCEDURES

TEST FLY ASHES

Sources and Types

Coal fly ashes investigated as part of this filtration study are described in Tables 12-14. Generally, the distribution of sources with respect to coal producing regions agrees with that sought at the inception of the program. However, additional weighting was assigned to western coals midway through the present study in view of considerable expansion in this market. Although the coal users were often found within their respective coal producing regions, there were occasions when the coal was hauled long distance (e.g., Wyoming to Texas by Southwestern Public Service), Table 12.

Most coals listed in Table 12 were burned after conventional pulverizing (~70 percent by weight passing a 200 mesh screen). Three coals were fired by stoker systems, one a utility design and the others commercial units. Because of the relatively small size of many stoker-fired boilers, <15 M, selection of three such ashes appears to overemphasize this category based upon its relatively small contribution to total power generation capacity. On the other hand, the sooty nature of some stoker effluents suggested that special filtration problems might arise.

In most cases, the fly ash samples were removed from the hoppers of baghouses used to control particulate emissions. Thus, the dust samples include some unknown fraction of solids, 10 to 40 percent, that failed to reach the fabric surface because of inertial or gravity separation. Only in one instance was a special field sample collected that represented the dust dislodged from the bags. Although a smaller size had been expected for the bag dust, laboratory measurements actually showed the opposite. Failure to obtain efficient and representative redispersal of the bag samples probably explains the apparent contradiction.

Fly Ash Properties

The color of the fly ashes varied from near white to very black with a broad intermediate spectrum ranging from gray to brown depending upon whether unburned coal or iron oxide dominated the mixture, Table 13. When the ash is fairly light colored, it is reasonable to assume that combustion has been nearly complete and that few uncombusted coal particles are present.

TABLE 12. FLY ASH SUPPLIERS AND COAL RANK, SOURCE, AND COMBUSTION SYSTEM

Sample number	Fly ash source	Coal description			Boiler ^a	
		Rank	Region	State	Mine/seam	Size MW Type
1	Southwestern Public Service, Amarillo, TX	Bit	VI	WY	Black Thunder Mine Wyodak-Anderson Bed	350(2) P
2	Crisp County, Cordelle, GA	Bit	III	GA	MaryLou Seam Jellico Seam	10 P
4	Kramer Station, NPPD Omaha, NE	Subbit	VI	WY	Adaville Seam, Lincoln County	25(3) P 37(1)
6	Texas Utilities, Mt. Pleasant, TX	Lignite	V	TX	Sulfur Springs, Wilcox Group Deposite	575(2) P
7	U.S. Steel, Provo, UT	Bit	VI	CO	Sunnyside and Somerset fields	90 P
8a	Amalgamated Sugar "A," ^b Nampa, ID	Subbit	VI	WY	Adaville Seam, Lincoln County	29 P
8b	Amalgamated Sugar "B," ^c Nampa, ID	Subbit	VI	WY	Adaville Seam, Lincoln County	28 P
9	Pennsylvania Power & Light Holtwood, PA ^d	Anthr., coke	I	PA	--	79 P
12	DuPont, Waynesboro, VA	Bit	II	KY, WV	--	76 P
13	Westinghouse, Hanford, WA	Bit	VI	UT	--	7 S
14	Case Medical Center, Cleveland, OH	Bit	I	OH	Georgetown Mine (Consol)	10 S
16	Republic Steel, Warren, OH	Bit	I	OH	Ohio No. 5 Seam	35 P
17a	Colorado Ute Electric Assoc., Nucla CO, (hopper sample)	Bit	VI	CO	--	39(3) S
17b	Colorado Ute Electric Assoc., Nucla CO, (bag shaken)	Bit	VI	CO	--	39(3) S

^aNumber in parenthesis refers to number of boilers of indicated size.^bRiley Pulverizer^cScott-Strong Pulverizer^dMixture of anthracite silts and petroleum coke

TABLE 13. ASH AND COAL PROPERTIES^a

Fly ash source	Fly ash color	Sulfur ^b percent	Proximate analysis, percent				Ash softening temperature °F	Heating value btu/lb
			Moisture	Volatile matter	Ash	Fixed carbon		
Southwestern Public Service, Amarillo, TX	Brown White	0.3-0.4	25-28	32-35	5.4-6.6	34.0	---	8,240-8,850
Crisp County, Cordelle, GA	Medium Gray	0.9	6.2	38.0	6.2	48.0	---	12,600
Kramer Station, NPPD Omaha, NE	Light Gray	0.5	18.8	35.5	3.3	42.4	~2,300	10,100
Texas Utilities, Mt. Pleasant, TX	Gray White	0.8-1.3	30.6	30.0	16-28	---	---	5,400-6,450
U.S. Steel, Provo, UT	Black	0.7	5.6	39.0	6.4	---	---	---
Amalgamated Sugar "A", Nampa, ID	Gray White	0.5	14.0	39.8	4.0	42.4	---	10,700
Amalgamated Sugar "B", Nampa, ID	Black	0.5	14.0	39.8	4.0	42.4	---	10,700
Pennsylvania Power & Light Holtwood, PA	Gray Brown	1.9	13.7	7.6	22.7	---	2,600	9,470
DuPont, Waynesboro, VA	Light Gray	1.1	6.7	28.6	13.2	51.0	~2,600	12,000
Westinghouse, Hanford, WA	Charcoal	0.5	8.3	38.0	9.2	44.5	2,260	12,400
Case Medical Center, Cleveland, OH	Black	1.8-2.7	5.7-6.0	---	6.9-8.9	50.0	2,170	12,600
Republic Steel, Warren, OH	Dark Gray	3.5	3.2	37.4	13.8	46.0	1,900	12,300
Colorado Ute Electric Assoc., Nucla CO, (hopper sample)	Black	0.7	6.0	31.0	11.9	51.0	---	12,000
Colorado Ute Electric Assoc., Nucla CO, (bag shakedown)	Black	0.7	6.0	31.0	11.9	51.0	---	12,000

^aSee Table 12 for additional data.^bFrom ultimate analysis.

TABLE 14. MINERAL CONSTITUENTS OF COAL ASHES^a

Fly ash source	Ash analysis, percent ^b								Percent sulfur
	SiO ₂	Al ₂ O ₃	TiO ₂	Fe ₂ O ₃	CaO	MgO	K ₂ O	Na ₂ O	
Southwestern Public Service, 48		16	1.5	6.1	20	3.2	1.5	0.52	0.3-0.4
Crisp County, Cordelle, GA 43-49		30-33	1.2-1.7	9.5-14	1.8-4.2	0.7-1.5	2.0-2.9	0.5-0.6	0.91
Kramer Station, NPPD 68 Omaha, NE		14	0.22	5.6	8.2	1.8		(2.1) ^c	0.45
Texas Utilities, Mt. Pleasant, TX 52		17	1.4	4.3	12.0	2.4	0.5	0.4	0.75-1.3
U.S. Steel, Provo, UT 51		35	--	5.3	4.0	0.5	0.7	0.2	
Amalgamated Sugar "A", Nampa, ID 68		14	0.22	5.6	8.2	1.8		(2.1) ^c	0.53
Amalgamated Sugar "B", Nampa, ID 68		14	0.22	5.6	8.2	1.8		(2.1) ^c	0.53
Pennsylvania Power & Light Holtzord, PA 52-68		25-37	1.1	4.6-6.7	0.2-1.5	0.5-1.2			1.9
DuPont, Waynesboro, VA 45		23	1.0	---	3.0	1.5		(4.5) ^c	1.1
Westinghouse, Handford, WA 54		15	0.76	6.3	1.3	2.4		(2.5) ^c	0.5
Case Medical Center, Cleveland, OH 33-53		19-30	0.6-1.1	19-35	0.4-3.7	0.3-0.8	0.4-2.0	0.1-0.3	1.8-2.7
Republic Steel, Warren, OH 32-44		22-29	0.6-1.2	29-40	1.7-1.8	0.2-0.7	0.9-1.0	0.1	3.5
Colorado Ute Electric Assoc., Nucla CO, (hopper sample) 58		32	1.2	5.1	1.5	0.2		(0.71) ^c	0.7
Colorado Ute Electric Assoc., Nucla CO, (bag shakedown) 58		32	1.2	5.1	1.5	0.2		(0.71) ^c	0.7

^aRefer to Tables 12 and 13 for further data on coal sources, properties, and applications.^bAsh analyses based upon assays from utility companies or from Keystone data (Reference 4) representing mine, seam, or coal field indicated as coal source by utility companies.^cRefers to combined percentage of K₂O and Na₂O.

The coal fly ash data summarized in Tables 12-14 have been regrouped according to the characteristics or parameters sought and the regions from which the parent coals were mined. The actual geographical distribution of coal sources and the ranges of values for the parameters listed in Table 15, Column 1, were in acceptable agreement with those specified tentatively in Table 10. Ranges of values cited for the B/A ratios, Table 15, were derived from the mineral assays for the various fly ashes given in Table 14.

Given the same mineral constituents and similar pulverizing (or size grading) equipment, an increasing blackness in the ash suggests incomplete burning and hence a fly ash that may prove difficult to collect by filter. If a coal is not sufficiently pulverized, however, in the presence of a highly oxidizing atmosphere (high air-to-fuel ratio) the gray to black color of a fly ash may result mainly from solid, unburned coal particles, 20 to 50 μm in diameter. Usually such particles tend to form a relatively porous dust cake that is readily permeable to gas flow as confirmed by low K_2 values.

In the present study, the coals represented many geographical areas such that the ash or mineral phase varied in both concentration and chemical composition, Table 14. Additionally, the presizing operations, whether pulverizing or rough screening for stoker-firing, may have differed considerably from plant to plant. As a result, the coal fly ash color per se offers only marginal guidance as to the ash filterability as discussed later under K_2 measurements.

Proximate analyses for the coals producing the test fly ashes as well as the percent sulfur also appear in Table 13. "As received" moisture contents, 3.2 to 30.5 percent; ash contents, 3.3 to 28 percent; volatile contents, 7.6 to 39.8 percent; fixed carbon, 34 to 51 percent; and sulfur contents ranging from 0.3 to 3.5 percent characterized the coals tested in this study.

FLY ASH AEROSOLIZATION

Test fly ash aerosols were generated with a National Bureau of Standards (NBS) type dust feeder.^{2,19} Dust descends from a storage hopper to a slowly rotating spur gear from which it is sucked into an air ejector by means of an aspirating tube, Figure 12. Clean, dried compressed air at 0.11 m^3/min STP (4 acfm) at 40 psig creates a violent shearing action within the ejector throat that re-disperses the bulk fly ash obtained from baghouse dust hoppers. Flexibility in supply aerosol volumes is attained by venting excess aerosol to waste lines. The actual flow desired for a specific experiment is extracted isokinetically from the test loop for transport to the filter assembly. The total air flow from the compressed air source plus that entrained by the ejector is roughly 0.22 m^3/min STP (8 cfm). During testing, all components of the test system are electrically grounded to facilitate charge losses from electrically charged particles and to minimize other potential electrostatic effects. Although a high level of dust break-up is attained with the NBS generator, the fly ash test aerosol always contains some agglomerated material not present in the parent dust. Thus, it is very important that the true size properties of the NBS generated particles be determined because the redispersed fly ashes will always be somewhat coarser

TABLE 15. CLASSIFICATION OF FLY ASH SAMPLES BY SELECTION CRITERIA

Characteristic:

● Coal producing region: ^a	I	II	III	IV	V	VI
No. of samples	3	1	1	0	1	8
● Boiler firing method:	Pulverized coal			Stoker-fired		
No. of samples	10			4		
● Sulfur content: ^b	Low (<1%)		Medium (1-3%)		High (>3%)	
No. of samples	9		4		1	
● Ash content:	Low (<5%)		Medium (5-15%)		High (>15%)	
No. of samples	3		9		2	
● Base/acid ratio:	Low (<0.17)		Medium (0.17-0.33)		High (>0.33)	
No. of samples	4		6		4	

^aRoman numerals refer to regions designated in Figure 1.

^bWhen a range of values is used to characterize a specific coal or ash property, the midpoint of that range is used to categorize the sample.

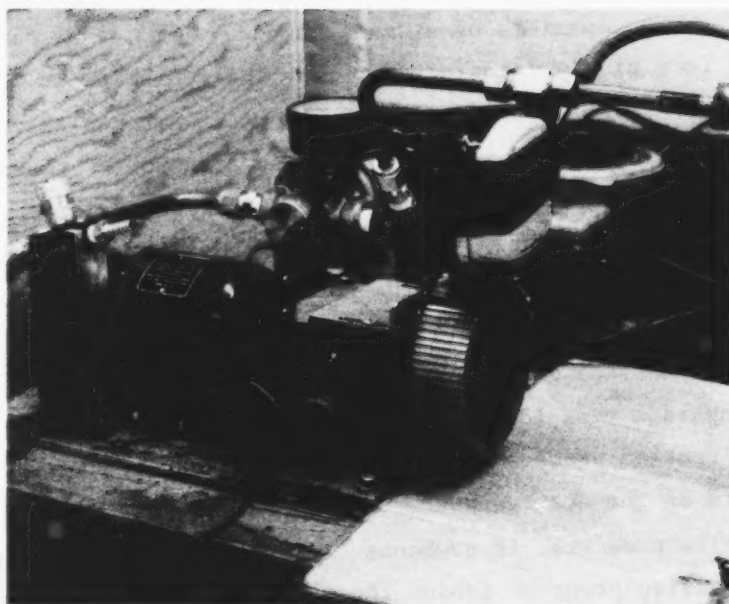


Figure 12. NBS type dust generator.

than the original airborne material. It is also important to dry the fly ash in a 70°C oven for at least 30 minutes before loading the generator dust hopper so that a uniform feed rate to the spur gear can be maintained.

FILTER TEST ASSEMBLY

The experimental program was designed so that filter performance tests involving fabric resistance, dust permeability, and particulate retention characteristics could be carried out insofar as possible on a bench scale. The latter approach affords the potential advantages of reduced testing time, higher measurement precision, less expensive equipment, and less space. The special test assembly used in this program consisted of a vertically aligned, 15 cm x 23 cm (6 in. x 9 in.) filter panel with a capability to handle air-to-cloth ratios up to 3 m/min (10 fpm). The filter medium was mounted in a metal frame that could be easily removed for inspecting, photographing, or weighing. As discussed in previous reports, the design of the filter assembly, Figure 13, simulates the normal approach conditions for the gas stream to be filtered while providing convenient access for determining the size properties and mass concentrations of the inlet and outlet fly ash particles. The dust hopper below the filter panel is sized to provide approximately the same air retention times found in full scale units. Roughly 30 to 50 percent of the entering dust load falls directly to the hopper as encountered in field units such that the particles actually reaching the filter face are generally smaller than those entering the hopper section.

Attention has been directed in prior studies to two disadvantages of flat test panels as compared to the usual cylindrical bag configurations. First, it is not possible to pre-tension the panels without resorting to an impractically complex apparatus. Second, the pressure gradient across the filter causes the panel to dish inward so that a uniformly sized pore structure cannot be maintained because of the warping. For present purposes, however, the above limitations do not affect the measurement of K_2 nor comparisons in fabric cleanability.

The bench scale approach provided a very convenient means to determine dust filtration properties including the specific resistance coefficient. During such testing, a fly ash aerosol at a constant inlet concentration, $\sim 5 \text{ g/m}^3$ (0.434 gr/ft^3), was passed through the fabric at selected face velocities, usually about 0.61 m/min in (2 ft/min). Dust accumulation upon the fabric was determined by intermittent system shutdown with removal of the test frame and fabric panel for weighing, or by calculating the areal density, W , from the filtration velocity, V , measured dust concentration, C_i , and testing interval, Δt , i.e. $W = C_i V \Delta t$. In the latter instances, a Millipore type filter holder was substituted for the cascade impactor shown schematically in Figure 13. Aside from making confirming measurements of the filter inlet concentration, the fly ash samples collected upon membrane filters or all-glass circles could also be used to determine fly ash K_2 values. Ordinarily, such sampling was continued until the fabric dust loading reached a weighable quantity, $\sim 200 \text{ g/m}^2$. The results of K_2 measurements performed by the above method versus those based on filtration through test panels, Figure 14, showed identical values (see Test Results).

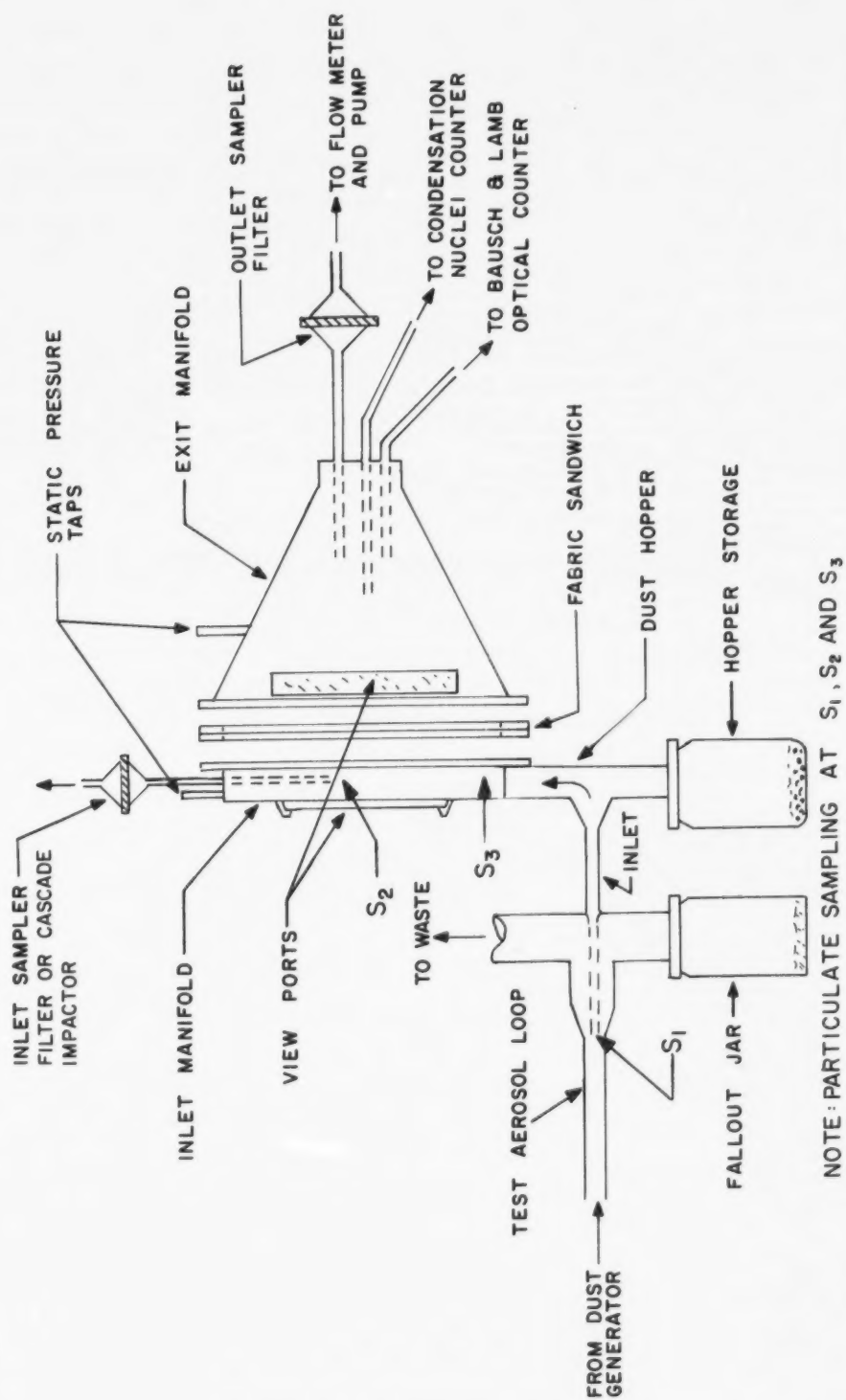


Figure 13. GCA bench scale fabric filter test assembly.

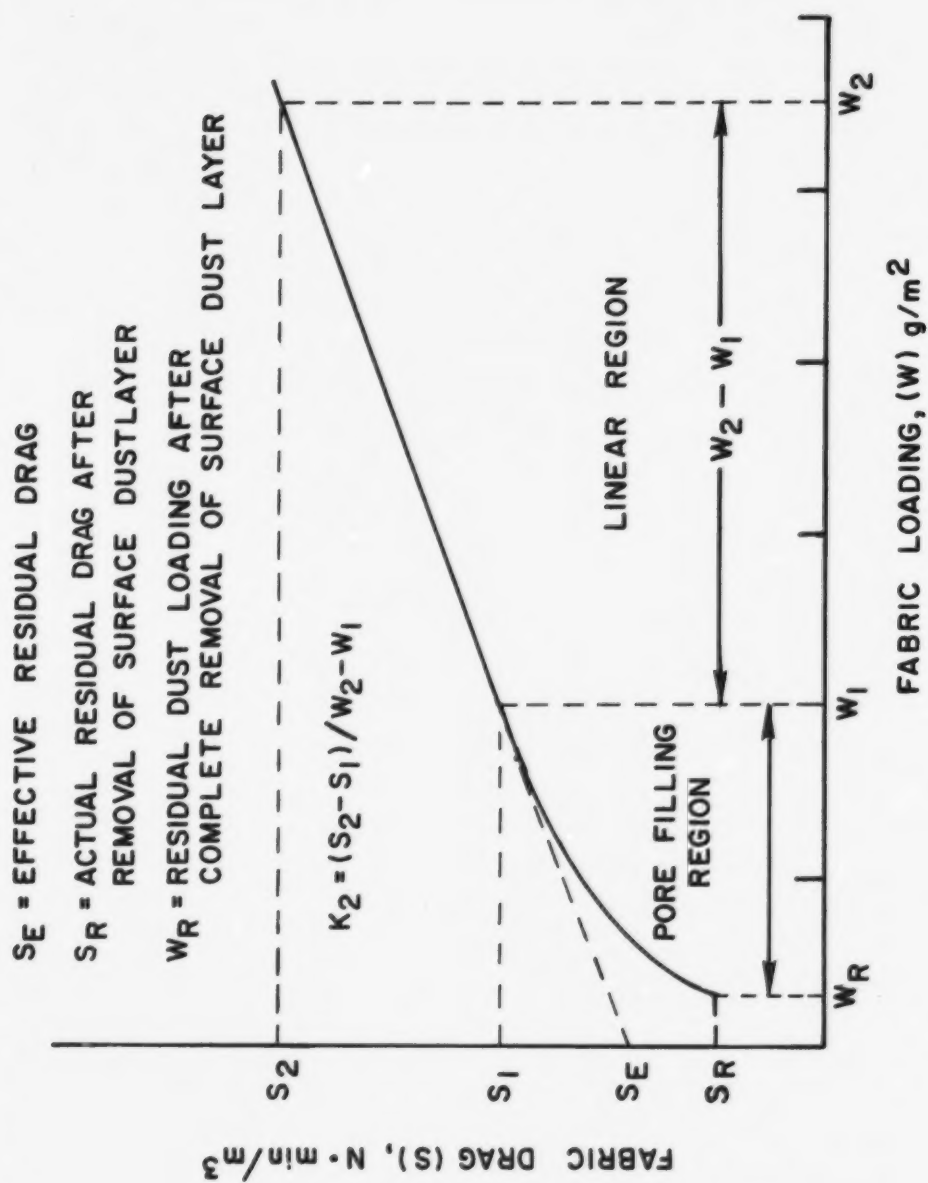


Figure 14. Typical drag vs. fabric loading curve used to estimate specific resistance coefficient, K_2 .

The advantage of this technique is that no initial curvature is encountered with the drag-fabric loading curves such as that displayed with some woven fabrics. As discussed in many prior reports and papers,^{1,2} it is necessary that the depressions in the fabric surface become filled before the characteristic concave down form of Figure 14 disappears. Although linearity is usually achieved beyond areal densities of 125 to 200 g/m², the degree and persistence of curvature frequently varies from one fabric to another or with different degrees of pore filling. Therefore, a complete drag versus loading trace (S-W) is needed to establish the linear section of the curve from which K_2 can be estimated.²⁰ Additionally, should there be an accidental variation in inlet dust concentration, the linear characteristics of the drag curve may be completely concealed.

On the other hand, if the dust is filtered through a relatively smooth surface such as displayed by most high efficiency sampling media, a sharp line of demarkation occurs between the dust layer and its supporting substrate. Therefore, except for the situation where a highly expanded dust cake may undergo progressive compression as the dust accumulates, the dust layer maintains a constant porosity throughout its depth. Under these circumstances, it is only required that the filter drag be determined before, S_f , and after, S_t , accumulating a known quantity of dust at a constant filtration velocity. Because most smooth-surfaced filter media exhibit significantly lower permeabilities, the curves will originate at higher pressure loss (or drag) values, Figure 15. A proposed field method for making direct determination of K_2 values utilizing the above approach is described in Appendix A.

FABRIC CLEANABILITY TESTS

Two approaches were investigated for estimating the ease or difficulty to be expected in dislodging the dust cake from the filter fabric. As discussed in prior studies,^{1,2,21} a special cleaning parameter, a_c , has been proposed to define fabric cleanability. The term a_c actually depicts the fraction of the surface dust layer dislodged from the fabric. During filtration at ambient temperatures at nominal 40 to 60 percent relative humidity levels and with no moisture absorbing (hygroscopic) problems, it has been observed that the actual separation of the dust occurs at the dust fabric interface where adhesive bonds are presumed to be the weakest. Detachment occurs when the adhesive force, F_A , which is a unique property of the dust-fabric combination of interest, is exceeded by the separating force, F_S . The latter quantity is defined as the product of the areal density for the dust deposit and the deceleration, a , to which it is subjected because of the motion imparted to the dust-fabric system by the cleaning action. The latter may be accomplished by a variety of commercial techniques that include bag collapse with reverse flow, mechanical shaking,^{20,21} or the increasingly popular pulse jet system.^{22,23}

Dust dislodgement may become a much more complex process, however, when high water vapor concentrations and hygroscopic particles interact at below-dew point conditions to produce sticky dust deposits. Under these conditions, field observations of fly ash deposits on glass bags failed to indicate any consistent cleaning pattern that would allow application of the " a_c " concept^{24,25} that depends upon dust layer separation at the dust-fabric interface.

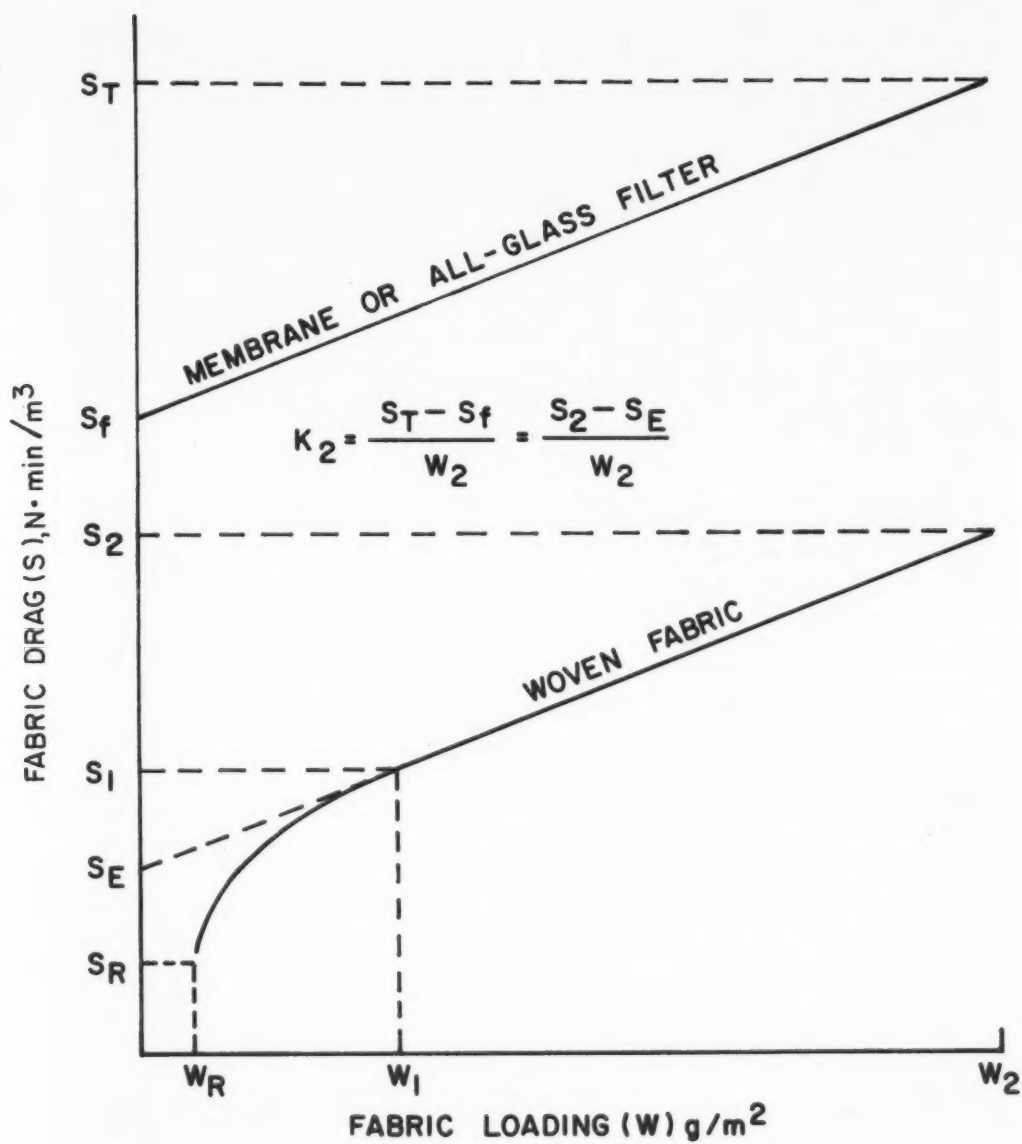


Figure 15. Schematic, drag vs. loading curves for same dust using membrane filters and woven fabrics.

Although all of the above cleaning methods have been evaluated in past GCA pilot plant studies,^{1,26} it was decided that the time and instrument requirements to perform such tests for many different fly ashes could not be satisfied in the present study. Therefore, various bench scale approaches were considered that would allow more experiments to be performed without compromising program objectives. The basic criterion was that the testing process should enable estimation of the relative cleanability of selected dust-fabric combinations. Under these conditions, a reasonable estimate of a_c might be made provided that an actual field measurement is available for one of two dust-fabric combinations investigated at the bench test level.

Collapse and Reverse Flow

A bench scale adaptation of field cleaning by bag collapse and reverse flow was used to estimate the relative cleanabilities of selected fly ash fabric combinations. Following shut-down of the aerosol generation system and the pump providing the filter flow (Figure 13), reverse flow air was flushed through the test panel at velocities of 0.15 and 0.61 m/min (0.25 and 1 fpm) for a period of 0.5 to 1.0 minutes. The amount of dust removed from the fabric and the fraction of surface area, a_c , from which the dust was dislodged were determined.

Concurrent measurements of K_2 were made based upon the observed drag-loading relationships. Total fabric surface loadings, W , at the instant of cleaning and the actual rates at which the dust was allowed to accumulate on the fabric were varied, the latter by changing dust feeder compressed air rates and/or the actual dust feed rate to the aspiration tube. It was observed that slightly coarser particles and slightly lower K_2 values resulted from increased dust loading rates. One infers from this observation that the larger the ratio of solids to suspending air, the less efficient the agglomerate break-up action becomes.

Simulated Pulse Jet Cleaning

A simulated pulse jet cleaning system was developed for use with the bench scale filter testing equipment shown in Figure 13. It was believed that the above cleaning approach might be easier to regulate than the collapse and reverse flow system, thus permitting better comparisons of fabric cleanability. At the same time, it was also planned to employ this equipment in a parallel study whose primary objective was to facilitate predicting pulse jet filter performance.

The apparatus designed for this program bears some similarity to a system described by Lefkowitz for comparisons of felted fabrics.²⁷ An attempt was made, however, to introduce a scaling factor that might lead to better correlations between bench and pilot scale cleaning systems. Based upon recent GCA studies,^{22,23} it was determined that the ratio of the pulse air volume, V_{ps} , (primary and secondary air) to the volume of the bag, V_b , was a key factor in establishing cleaning effectiveness. The rate of pressure change on the clean air side of the bag to the solenoid valve opening time is approximated by the ratio:

$$d(\Delta p)/dt \propto \frac{V_{ps} + V_b}{V_b}$$

In turn, the rate at which a felt bag and its surface loading decelerate following a rapid radial excursion due to pulsing is also proportional to $d(\Delta p)/dt$, all other things being equal.^{22,23}

The preceding analysis suggested that maintenance of similarity for bench scale pulse cleaning might be attainable by adjusting the pulse volume to compensate for the reduced air space behind the filter (which corresponds to the bag volume). The air volume behind the filter in Figure 16 is roughly 3.4 liters as compared to 12.6 liters for the 1.22 m x 11.4 cm bags used in prior GCA pilot test equipment.²⁶ Hence, the pulse jet volume for the bench apparatus was reduced to 0.27 times that used in typical bag tests.

Although a corresponding reduction in nozzle cross-sectional area meets the reduced jet delivery requirements, a more uniform distribution was obtained by drilling three 2.8 mm holes in a distributor ring as shown in Figure 16, whose total area was 0.27 times that of a standard commercial nozzle (9.21 mm diameter). Additionally, the ring openings were directed to the rear of the housing to minimize highly localized jet impingement on the test panel. During laboratory tests, the controls were set for a 0.06 sec pulse duration and compressed air pressures were varied from 20 to 40 psig. As described under Test Results, the cleaning of Dacron felt panels with the above system was roughly equivalent to that obtained with full-scale bags.

PARTICLE SIZE MEASUREMENTS

Particle size determinations were made by Andersen (Mark 3) cascade impactor sampling of the inlet airstream immediately before and at the center of the fabric test panels. As reported in many past studies,^{1,2,22,,26} extraction of the fly ash samples at the above location provides a reasonably accurate description of the dust actually reaching the filtration surface. Previous measurements, both in the laboratory and in the field, have shown that extensive duct length and the usual bends or other flow perturbations associated with breechings, adapter sections, baffles, or tangential entries can cause significant reductions in dust concentration and particle size properties as the result of gravitational settlement or inertial separation. Thus, although the usual upstream sampling site selected for field measurements may well be the only available location, its value for precise estimation of critical size parameters relating to filtration potential can be seriously questioned.

Laboratory tests have indicated that the fraction of dust depositing in the vertical sampling line (25 cm long x 0.8 cm in diameter) leading to the externally placed cascade impactor (Figure 13) is small compared to the total dust captured on the Andersen impactor stages and the back-up filter. It is recognized that the aerosols produced during the laboratory program by compressed air re-suspension of bulk fly ash may not give a true picture of the size of the parent dust particles originally collected by field fabric systems. Based upon many past studies 1, 10, 18, 19, 26, it is suspected that a somewhat coarser particle size will characterize most test re-dispersions

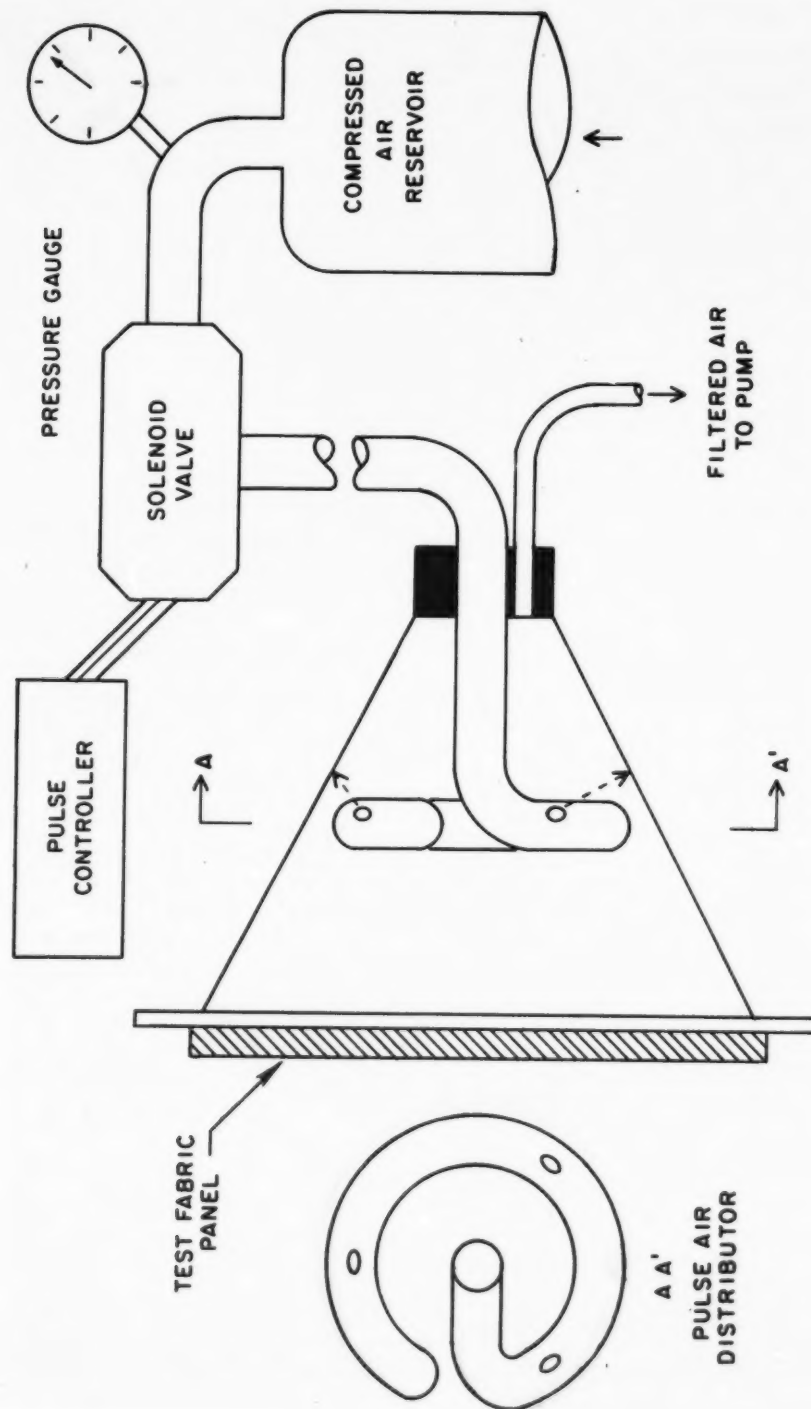


Figure 16. Schematic simplified pulse cleaning system. See Figure 13 for complete test assembly.

regardless of the pressures used by compressed air ejector nozzles because of the extreme difficulty in disassociating agglomerated particles. The size properties defined during panel tests, however, are believed to present a realistic description of the dust reaching the laboratory filters.

During the current program, replicate samples were collected for each fly ash under investigation. Inlet dust concentrations were maintained in the 1.5 g/m³ range such that sampling periods were restricted to 1 to 2 minutes to avoid overloading the collecting stages. The total air flow approaching the filter holder was approximately 0.028 m³/min with half entering the Andersen impactor while the remainder passed through the filter panel.

All filters and/or substrates were weighed on a Mettler balance with successive weighings agreeing within 0.1 mg accepted as equilibrium values. The manufacturer's calibration data for stage jet diameters and for the inertial impaction parameter (V_{ψ}) were used to calculate cut diameters (diameter of the particle that is collected with 50 percent efficiency) for each impactor stage. An iterative procedure, adapted for a programmable pocket calculator,²⁸ was used for these calculations.

Cumulative particle size distributions were plotted on log-probability paper for the two impactor sizings performed for each fly ash. A straight line was fitted to each plot with the data points describing the upper 90 percentile of the mass distribution used to determine the curve location. The reason for this approach is that the larger particle sizes appear to dominate the basic pore structure in the dust cake. Estimated values for the aerodynamic mass median diameter (aMMD), the geometric standard deviation (σ_g), and the specific surface parameters (S_o) were derived from these size distribution curves. The specific surface parameter, as will be shown later, plays a key role in determining dust cake permeability as defined by the specific resistance coefficient, K_2 .

SECTION 6

RESULTS

INTRODUCTION

A major objective of this study was to determine whether one could utilize data relating to chemical constituents and physical properties of U.S. coals to predict the filtration characteristics of their respective fly ashes. As pointed out in prior reports and papers discussing requirements for modeling filter system behavior, knowledge of the permeability of a fly ash is essential to ascertain operating pressure losses across dust-laden fabrics.^{1,2,20,21,24,26} Additionally, the degree of difficulty associated with the periodic cleaning of the fabric also plays an important role in defining the type and extent of the required cleaning as well as influencing operating pressure loss across the system.

The fly ash permeability properties have been defined by the parameter, K_2 , otherwise known as the specific resistance coefficient. The term K_2 is the proportionality constant in the classical equation used for predicting the pressure drag, S , across a dust layer of areal density W , where P is the pressure loss, and V is the filtration velocity (or air-to-cloth ratio).

$$S = P/V = K_2 W \quad (1)$$

When P is expressed in Pascals (N/m^2), V in m/min , and W in g/m^2 of filtering surface, the units for K_2 are $N \cdot min/g \cdot m$.

In the filtration model designed by GCA,^{1,2,21} the term a_c , which is used to designate fabric cleanability, describes the fraction of the fabric area from which the surface dust layer has been removed. It ranges from roughly 0 to 0.15 for collapse and reverse flow cleaning to 0.5 for vigorous mechanical shaking, and is essentially 1.0 for a well functioning pulse jet system provided that there are no moisture problems.²³ In the filtration model, it determines how the gas flow is partitioned between cleaned and uncleaned regions for which the respective drag values are indicated as S_c and S_u . Overall fabric drag S , is computed by iterative procedures from the equation.

$$S = \left(\frac{a_c}{s_c} + \sum_{i=1}^n \frac{a_{v_i}}{s_{v_i}} \right)^{-1} \quad (A) \quad (2)$$

where a_c refers to the fraction of cleaned surface, a_{ui} to the i th uncleaned fractions, and S_{ui} indicates the drag of the i th uncleaned region.^{1,2}

At the start of the present study, both theoretical and empirical approaches had been used for making rough estimates of K_2 based upon particle size measurements for the dust approaching a filter and the static and kinetic properties of the supporting gas streams. It was recommended that direct measurements, preferably in the field or at least with pilot scale laboratory systems, be used to estimate both K_2 and a_c values because of the absence of dependable measurements. It should be noted that available guidelines prior to the present program dealt specifically with fly ash properties and not those of the parent coals. Although it was possible to infer how raw coal properties, the manner of coal crushing, and method of combustion might affect fly ash filterability as discussed in Section 3, there was no way to apply these data to develop any formal mathematical relationships. It was surmised, however, that the potential for useful correlations might lie in the relationships between a multiplicity of coal properties and the measured size properties of the fly ashes. For example, K_2 values for several fly ashes and other mineral dusts were observed to correlate well with the size properties of the ash.

In the following paragraphs, we have presented the results of K_2 determinations and particle size measurements for the various fly ashes listed in Tables 12 through 14.

FLY ASH SIZE PROPERTIES

Particle size parameters were determined by Andersen Mark III cascade impactor wherein samples were extracted via a short probe from the central section of the inlet manifold, Figure 13. Collection at this location provided a good approximation of the size characteristics of the fly ash actually reaching the filter surface. Cumulative size distributions of the data were plotted on log-probability paper for the two impactor sizings performed for each fly ash. The aerodynamic mass median diameter (a_{MMD}) and the geometric standard deviation (σ_g) were estimated for each pair of curves, which showed excellent agreement in most cases.

Most tests were conducted at an air-to-cloth ratio of 0.61 m/min (2 ft/min), a flow rate typifying many reverse-air-cleaned systems. The same flow rate prevailed during the tests conducted to estimate specific resistance coefficient, K_2 . Figure 17 depicts the size distribution curve for redispersed fly ash from southwestern Public Service, Sample 1. The excellent replication of size parameters derived from two separate tests was also noted for the other coal fly ashes evaluated in the program (see Appendix B).

The linear fits to the paired data points were performed visually and based upon the assumption that those particles representing the upper 90 percentile of the solids mass would dominate the porosity structure of the dust cake. Valid or otherwise, this approach has afforded good correlations with measured K_2 values. In many instances, however, the complete data point arrays showed only minor deviations from linearity.

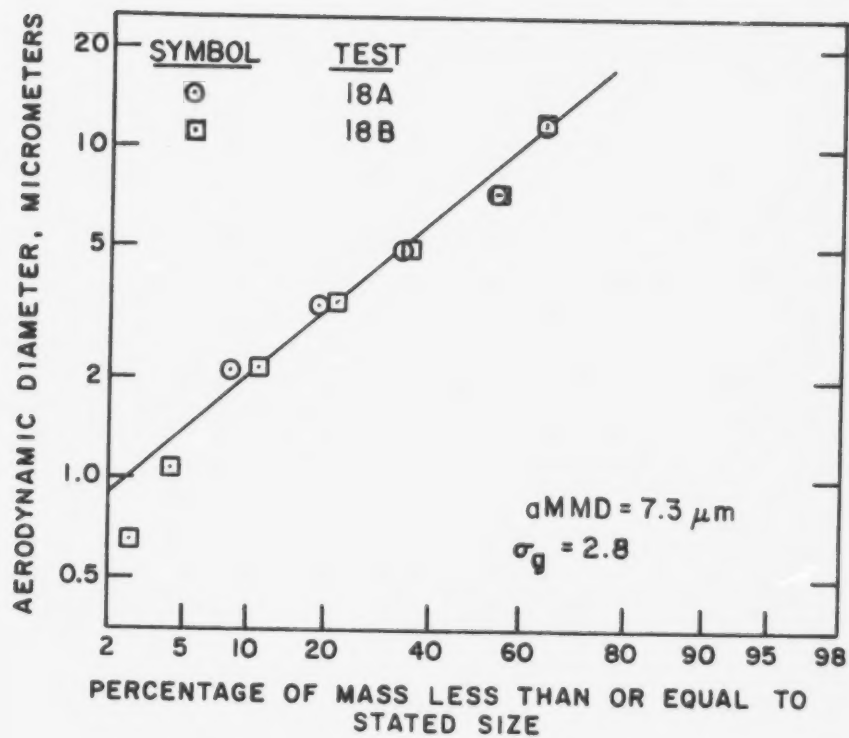


Figure 17. Particle size distribution for Southwestern Public Service resuspended fly ash, Andersen Mark III impactor measurements. Sample 1.

Based upon the calibration of the Andersen impactor, the median value estimated graphically from Figure 17 represented the aerodynamic mass median diameters for unit density particles. Thus, in computing the specific surface parameter, S_o , which is intended to reflect the actual channel and interstitial surface properties of the dust layer, it has been necessary to convert the aerodynamic values to those corresponding to fly ash particles with an assumed density of 2 g/cc.

Table 16 summarizes the experimentally determined and derived values for the fly ash size parameters, K_2 values, and the Base/Acid ratios calculated from best estimates of the respective fly ash assays in Table 14. Moisture, sulfur content, total ash, and volatile fraction are also indicated for convenient reference. In Table 17, correlation coefficients are presented for the relationships between K_2 and the variables cited above.

SPECIFIC RESISTANCE COEFFICIENT, K_2

K_2 versus Particle Size

All K_2 measurements were performed with the test apparatus described previously in Figure 13. Actual K_2 values were computed from the drag versus fabric loading curves of the type shown in Figure 18. Curves for all the test fly ashes are presented in Appendix C. Since the filter fabric (twill weave glass) used during these tests contained a residual dust holding, W_R , that could not be removed by conventional cleaning techniques, the drag value at the initiation of each test reflects the characteristic residual drag (S_R) for the cleaned fabric with its residual dust holding. The initial curvatures for the drag curves, which have been discussed extensively in the literature,²⁰ are not important because it is the near linear right hand segment of each curve that is used to compute K_2 values.

An adaptation of the classical Kozeny-Carman relationship, investigated by Rudnick and First²⁹ and later modified for GCA applications,³⁰ has been used to estimate K_2 on the basis of theoretical considerations:

$$K_2 = \frac{\mu S_o 2R}{6 \rho_p C_c} \quad (3)$$

where μ is the gas stream viscosity, S_o the specific surface parameter, R a complex function of dust cake porosity, ρ_p the discrete particle density, and C_c the Cunningham-Millikan slip correction. S_o characterizes the surface to volume ratio for the polydisperse particle system constituting the dust cake. S_o is readily computed from the size parameters derived from cascade impactor measurements, provided that the cumulative size curve may be approximated by a logarithmic-normal distribution; i.e.,

$$S_o = \frac{6}{MMD} \cdot 10^{1.151 \log^2 \sigma_g} \quad (4)$$

TABLE 16. MEASURED AND COMPUTED VALUES FOR VARIOUS FLY ASH PARAMETERS

Fly ash source ^c	Coal constituents, percent				Fly ash charge effects	Experimental values ^a					
	Sulfur	Moisture	Volatile matter	Ash		K ₂ N/min/g-m	aMMD		S ₀ ² x 10 ⁻⁸ cm ⁻²		
							μm	μm			
Southwestern Public Service, Amarillo, TX	0.3-0.4	25-28	32-35	5.4-6.6	0.48	No	2.82	7.3	5.2	2.8	3.9
Crisp County, Cordelle, GA	0.9	6.2	38.0	6.2	0.17-0.33	Yes	1.61	7.5	5.3	2.5	2.96
Kramer Station, NPPD Omaha, NE	0.5	18.8	35.5	3.3	0.72	No	3.79	5.9	4.2	2.3	4.14
Texas Utilities, Mt. Pleasant, TX	0.8-1.3	30.6	30.0	16-28	0.28	Yes	0.89	9.7	6.9	2.3	1.53
U.S. Steel, Provo, UT	0.7	5.6	39.0	6.4	0.13	No	1.73	8.6	6.1	2.3	1.95
Amalgamated Sugar "A", ^d Nampa, ID	0.5	14.0	39.8	4.0	0.22	Yes	1.49	7.7	5.4	2.5	2.81
Amalgamated Sugar "B", ^d Nampa, ID	0.5	14.0	39.8	4.0	0.22	No	4.63	6.7	4.7	2.8	4.63
Pennsylvania Power & Light Holtwood, PA ^e	1.9	13.7	7.6	22.7	0.07-0.5	No	0.98	9.6	6.8	2.2	1.45
DuPont, Waynesboro, W. VA	1.1	6.7	28.6	13.2	0.28	Yes	1.66	4.7	3.3	2.2	6.07
Westinghouse, Hanford, WA	0.5	8.3	38.0	9.2	0.35	Yes	4.55	8.2	5.8	3.7	5.93
Case Medical Center, Cleveland, OH	1.8-2.7	5.7-6.0	---	6.9-8.9	0.25-0.5	Yes	4.52	6.5	4.6	3.8	10.1
Republic Steel, Warren, OH	3.5	3.2	37.4	13.8	0.5-1.0	No	2.12	9.6	6.8	2.3	1.56
Colorado Ute Electric Assoc., Nucla CO, (hopper sample)	0.7	6.0	31.0	11.9	0.08	Yes	3.40	7.4	5.2	3.2	5.08
Colorado Ute Electric Assoc., Nucla CO, (bag shakedown)	0.7	6.0	31.0	11.9	0.08	Yes	1.93	8.2	5.8	3.0	3.58

^aMMD and S₀² are derived values obtained by the following relationships:
 $MMD = aMMD/\sqrt{p}$ where $\frac{a}{p}$ is assumed to be 2 g/cm³ for coal fly ash

$$S_0 = 6/MMD (101.151 \log^2 \frac{a}{p})$$

^bBased on mineralogical data, Table 14.

^cSee Tables 12 through 14 for more details on coal properties.

^dSame coal but with different pulverizers, see Table 11.

^eAbnormal fuel-mix of anthracite silt and petroleum coke.

TABLE 17. CORRELATION COEFFICIENTS FOR K_2 WITH VARIOUS COAL AND FLY ASH PROPERTIES

Variable	Correlation Coefficient (r)
Specific surface parameter, S_G^2 (cm^{-2})	0.733 ^a
Sulfur in coal, %	-0.146
Ash in coal, %	-0.575 ^a
Moisture in coal, %	-0.148
Volatile matter in coal, %	0.450
Base/acid ratio	-0.050

^aIndicates that correlation coefficient is statistically significantly different from zero (p 00.05).

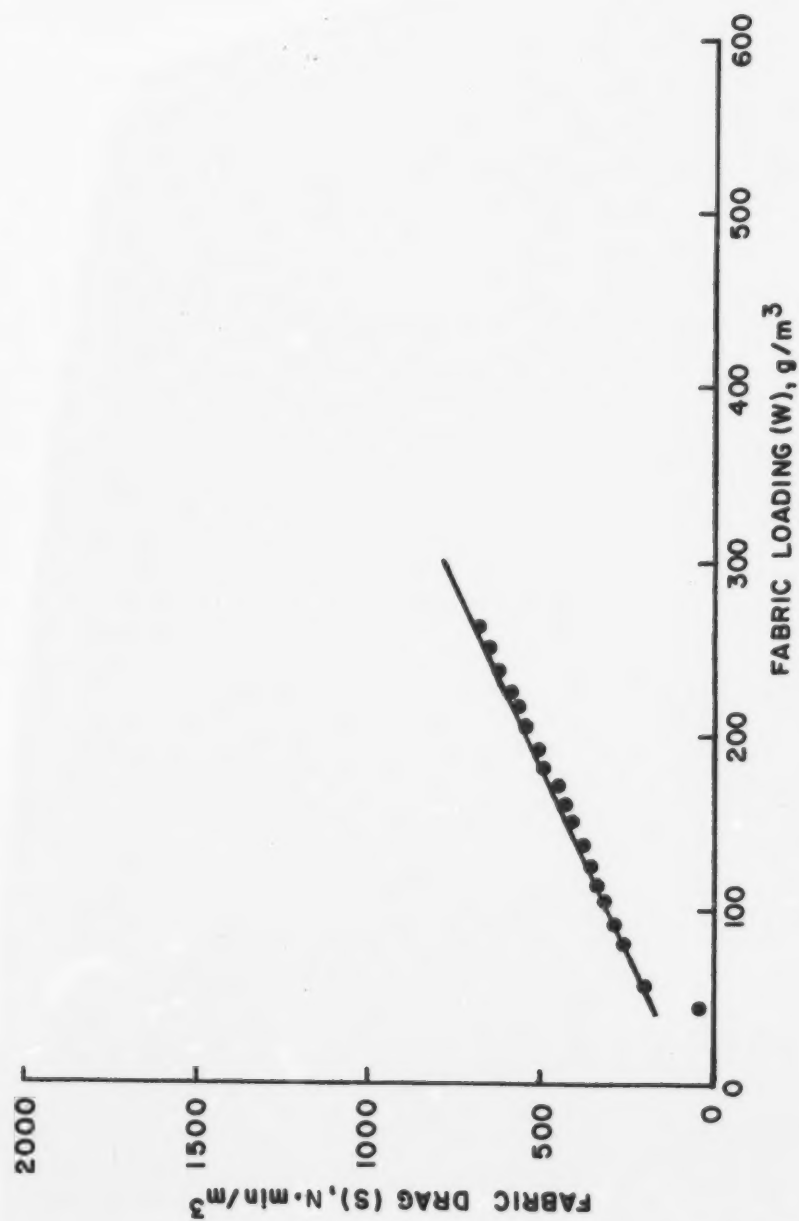


Figure 18. Drag vs. fabric loading, Southwestern Public Service's fly ash, $A/C = 0.61$ m/min.

where MMD refers to the true mass median diameter and σ_g is the geometric standard deviation. As emphasized in earlier studies,³⁰ Equation (3) is of limited use as a predictor of K_2 , since small (~10 percent) changes in porosity can lead to gross (~50 percent) errors in K_2 predictions. If all terms in Equation (3) remain constant except S_o , an arithmetic plot of K_2 versus S_o^2 should appear as a straight line with its origin at zero. One infers from this relationship that K_2 must increase as the dust becomes progressively finer and the dust cake less permeable to gas flow. In fact, the actual K_2 versus S_o^2 graph shows a strong positive correlation as forecast by theory (Figure 19). The linear regression line developed by a least squares data analysis is defined by:

$$K_2 = 0.93 + 0.42(S_o^2) \quad (5)$$

where K_2 is expressed in N·min/g·m and S_o^2 in μm^{-2} . The r^2 value for this equation, 0.54, (the fraction of the variation in K_2 that is "explained" by the equation) is statistically significant at the $p = 0.003$ level.

Despite the favorable statistics, the scatter of the data from which Equation (5) was calculated restricts its use as a predictive tool. The point scatter is attributed to a combination of unavoidable experimental errors and real differences in particle shape, charge, and density that can also cause significant variations in cake porosity. Based on the observed point scatter, the estimated 95 percent confidence envelope about the regression line has been developed, as shown in Figure 19. If, for a certain fly ash, S_o^2 were measured as $5.0 \times 10^{-8} \text{ cm}^{-2}$, Equation (5) would predict a K_2 value of 3.0 N·min/g·m as a "best estimate." However, were K_2 for this fly ash to be determined by actual measurement, there is a 95 percent chance that its true value would fall within the range 0.85 to 5.2 N·min/g·m. Consequently, Equation (5) cannot be used for design purposes, despite the statistically significant K_2 - S_o^2 correlation.

EFFECT OF BOILER TYPE AND FIRING METHOD ON K_2

The method of coal firing usually influences fly ash size properties, with a stoker-fired boiler producing a coarser fly ash than that generated by a pulverized-fired or a cyclone boiler. Accordingly, one expects to see a higher K_2 value for a pulverized coal fly ash compared to that for a stoker fired effluent. Unfortunately, only semi-quantitative relationships could be inferred from the present observations, first because of limited data, and second, because additional factors not defined in this study can also affect the size properties; e.g., air/fuel ratio, load level, system geometry, gas residence time, and settlement losses.

The mass median diameters presented in Table 16, which were determined for resuspended fly ashes, do not show any striking differences when grouped according to firing method, although all four stoker-fired ashes were slightly more polydisperse. The latter effect is assumed to be the main reason for the greater S_o^2 and hence greater K_2 values for the stoker-fired ashes; i.e., 3.6 N·min/g·m versus an average of 2.2 N·min/g·m for pulverized coal ashes. After adjustment to a common S_o^2 value, however, this K_2

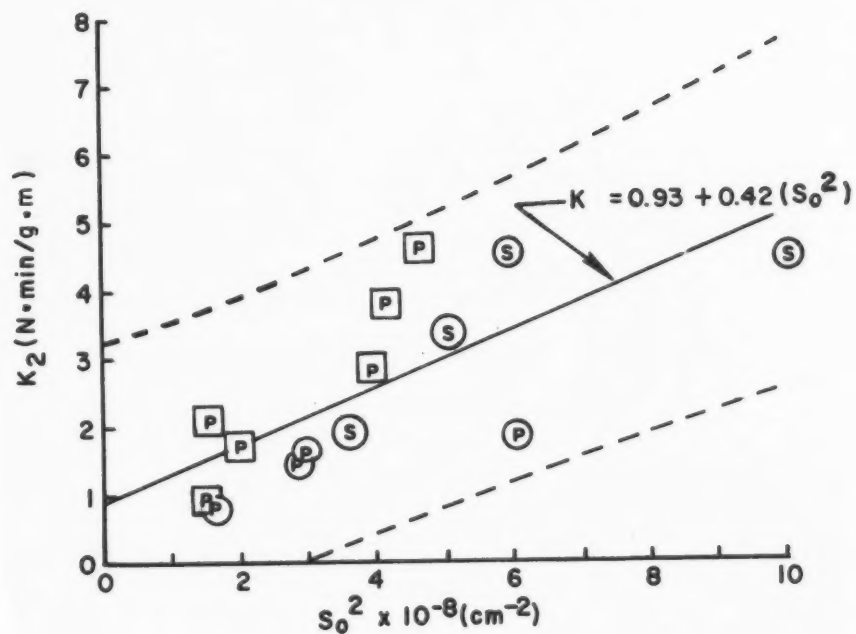


Figure 19. Specific resistance coefficient (K_2) vs. specific surface parameter (S_0^2) with 95 percent confidence interval indicated by dotted lines. (P) and (S) refer to pulverized and stoker firing. Circles delineate charge effects.

difference was shown to have no statistical significance. It is emphasized, however, that for the above comparisons to be valid in the field, the expected differences in size properties between the original and resuspended states of the fly ash must be the same for both firing methods.

EFFECT OF ELECTRICAL CHARGE ON K_2

The presence of ionizable salts in fly ash may produce secondary filtration effects due to electrical charging. Since the resultant charges induced by thermal dissociation or contact electrification in the combustion zone are essentially unipolar, particle repulsion effects within the close confines of the dust layer may afford the advantage of lower K_2 (and decreased pressure loss) due to increased porosity. It can also be argued that the extent to which charges induced on a fabric are able to leak off, may also affect dust dislodgement characteristics with a charge accumulation causing increased adhesion.

Electrostatic charging is often a problem in the resuspension of bulk dusts by high velocity aspiration. Although all metal components of the test system in Figure 13 were electrically grounded, there was still evidence of electrostatic charging and wall deposition for some of the fly ashes tested. Although no attempt was made to quantify the degree of apparent charging, samples were categorized as to the presence or absence of visible electrostatic deposition in the test system. According to Figure 19, it appears that these eight samples (circled symbols) tend to lie below the six samples (open symbols) displaying no obvious electrostatic effects. That is, for a fixed value of S_0^2 , fly ashes exhibiting electrostatic effects also possessed significantly (statistically) lower K_2 properties. However, except for the fact that four of the eight samples also represented stoker-fired combustion, electrostatic behavior of the fly ashes could not be related to any other coal or ash properties. It has not been determined whether there is some intrinsic fly ash property that predisposes it to the accumulation of electrostatic charge or whether this behavior is an artifact of the experimental measurement system. Thus, although the electrostatic properties of fly ash as observed here are useful in explaining observed differences in K_2 , they provide no guidance in predicting them.

EFFECT OF COAL SULFUR CONTENT ON K_2

The manner in which the sulfur content of coal affects fly ash filtration properties is not clearly understood, although it has been established that sulfur in various forms can affect ash fluid properties. The presence of suspected sulfate salts, as shown by the SO_3 assays for the coal ashes, may decrease ash softening and fluid temperatures, or at least broaden the temperature range over which an ash converts from the solid to the fluid state.

If the viscosity of the molten ash is lowered sufficiently, it is reasonable to expect that gas stream turbulence and shearing action might lead to droplet breakup. On the other hand, those particles that have been converted to the liquid phase but still remain highly viscous (and sticky) may serve as irreversible collision sites for small particles undergoing Brownian

diffusion. Under these conditions, it appears that the presence of sulfates might either increase or decrease particle size parameters depending upon which mechanism prevails.

If the coal sulfur content is due mainly to iron pyrite in the raw coal, significant separation of FeS_2 during coal upgrading will reduce the "basic" phase of the ash and hence diminish the base-to-acid ratio. Under these circumstances, one might expect an increase rather than a decrease in the softening temperature. With less chance for particle adhesion and less reduction in particle size due to droplet breakup, slightly coarser particles and hence, lower K_2 values, might be predicted. Although analyses of the 14 samples suggest an inverse effect, the low value for the correlation coefficient (-0.05) precludes assigning any statistical significance to it. It is possible that examination of more coal samples, in which a wider range of sulfur contents is exhibited, may afford better resolution of the K_2 -sulfur correlation. Since sulfur content is usually an easily measured parameter, its use in a workable K_2 -sulfur relationship is attractive.

EFFECT OF COAL ASH CONTENT ON K_2

The effect of ash content upon ash fusion properties was examined on the premise that an increase in coal ash content might conceivably result in less heat transfer to individual mineral particles for a fixed energy input, thus slowing particle transition to the viscous and fluid states. Reduced melting might be expected to yield generally coarser and more irregularly-shaped fly ash particles. Regardless of any possible impact upon particle size parameters or softening temperatures, filtration demands (cloth and fan capacity) will automatically relate to the volume of fly ash produced which, in turn, should depend upon the amount of mineral present in the parent coal.

Data pairs representing 14 samples appear to support the proposed high ash effect; i.e., a coarser dust. Other than specific surface properties, coal ash content was the only other variable that correlated significantly with measured K_2 values. Although the data exhibit considerable scatter, Figure 20, K_2 values are seen to decrease with total ash content as predicted. The K_2 versus ash content correlation is too broad to be of any real value. When combined with the specific surface parameter, S_o , in a multiple regression analysis, the resulting equation is:

$$K_2 = 2.04 + 0.345 (S_o^2) - 0.079 (\% \text{ Ash}) \quad (6)$$

The r^2 for Equation (6) is slightly larger than that for Equation (5), 0.65 versus 0.54, and the ratios for predicted to measured K_2 values for this equation fall within a slightly narrower band than those for Equation 5. It should be noted, however, that the coefficient for (% ash) just misses statistical significance at the $p = 0.05$ level.

BASE-TO-ACID RATIO

Although a number of characterizing ratios derived from the chemical constituents of fly ash were investigated initially, only the base-to-acid (B/A) ratio appeared to offer any predictive capabilities. The basic

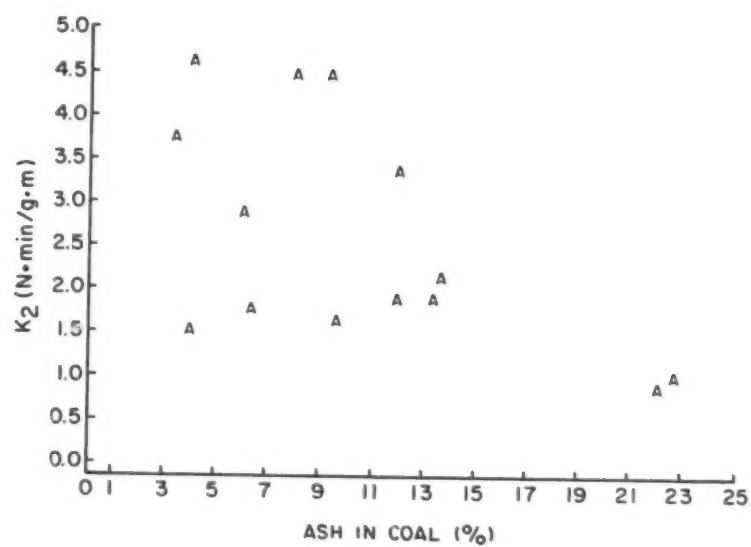


Figure 20. Dust cake specific resistance coefficient (K_2) versus percent ash in coal.

components of the ash are Fe_2O_3 , CaO , MgO , Na_2O , and K_2O , while the acidic components are SiO_2 , Al_2O_3 , and TiO_2 . Minimal ash melting points and fluid temperatures accompanied by a more rapid transition from the solid to the liquid phase are observed with a 1:1 mix of basic and acidic components. As the B/A ratio becomes larger or smaller than 1/1, melting points and fluid temperatures rise. This trend is roughly symmetrical on either side of the unity ratio, depending only on the relative difference between basic and acidic components. Thus, the effect of a B/A ratio of 1/2 is approximately the same as that for a ratio of 2/1. B/A ratios were calculated for 93 ash samples (representing all 6 coal producing regions).¹³ When these ratios were compared with their corresponding ash softening temperatures, the correlation coefficient was very high ($r = 0.81$, $p = 0.001$).

Although the base-to-acid ratio is clearly an indicator of ash melting and fusion properties, the expected link between melting and fusion properties and effluent particle size and K_2 could not be discerned, as discussed earlier in this report. Correlation coefficients for B/A with both K_2 and S_g^2 were approximately -0.2, well below the level of significance for a sample of this size.

EFFECT OF FILTRATION VELOCITY ON K_2

Limited tests were performed to determine the effect of filtration velocity on K_2 for comparison with previous measurements on coal fly ash. According to past tests with a coal fly ash produced by a cyclone-fired boiler,* the K_2 -V relationships could be expressed functionally as $K_2 \propto V^{0.5}$ when the aMMD and σ_g values for the ash were 6.38 μ m and 3.28.^{1,2} On the other hand, the K_2 response to velocity increases appeared to be much less for the coal fly ash supplied by Southwestern Public Service, Table 16, where aMMD and σ_g values were 7.3 μ m and 2.8, respectively.

Since no charge effects were observed in the laboratory with either fly ash and the size parameters were roughly the same, there was no obvious explanation for the decreased velocity exponent n ; i.e., $K_2 \propto V^{0.2}$. The current results appear to confirm that n may range from 0.2 to 1.0 depending upon the dust^{1,29,31} and other factors that remain to be identified.

FLY ASH CLEANING CHARACTERISTICS

Dust Dislodgement versus Particle Size

It has been reported earlier that the cleaning parameter, a_c , is a unique function of the fly ash-fabric combination of interest.^{1,2} Additionally, it is anticipated that electrical charge phenomena and certainly the size properties of the fly ash (given the same fabric) should have some bearing on the adhesive forces binding the surface dust layer to the fabric.

*Public Service Company of New Hampshire, Bow, New Hampshire.

Insofar as particle size is concerned, any reduction in diameter will increase both the total number of particles in the dust and the number of particles making fiber contact per unit area of filter. In the case of a polydisperse distribution, the number of contacts per cm^2 (assuming contiguous particles in a square array) are best represented as an inverse function of the volume diameter (d_v) squared. When d_v is expressed in centimeters, the total particle-to-fabric contacts per cm^2 of filtering surface, N , is defined as $1/d_v^2$ assuming that particles are distributed in a square array with their centers in the same plane.

Since the adhesive force in dynes between a single particle and a large diameter fiber may be approximated by the relation $F_A = 100 d_v$, the total adhesive force acting upon 1 cm^2 of filtration surface becomes:

$$F_A = (d_v^{-2}) 100 d_v = 100/d_v \text{ dynes} \quad (7)$$

if all particles in the dust layer adjacent to the fabric make contact with the yarns. Furthermore, given a well compacted dust cake, the estimated adhesive force between adjacent dust layers would be 10^5 dynes/cm^2 if a value of 10 m is assumed for d_v .

Because of the significant concavities or depressions associated with fabric surfaces in which the yarn dimensions (~ 200 to $700 \text{ }\mu\text{m}$ diameter) dominate the surface contours, one expects to find far fewer adhesive contacts. This is demonstrated by the bridging structures that evolve as isolated dust chains ultimately interlock to form the substrate for further dust deposits; thus, one can conceive of interfacial adhesive bonds that are 100 and up to 1,000 times smaller than those within the dust cake proper.

The estimates of adhesive forces bonding coal fly ash to glass and cotton fabrics, respectively (Figure 21), appear to signify a broad range of interfacial adhesive strengths.²¹ With 50 percent removal of the surface dust layer, it appears that half the dust adheres to the glass fabric with a force of 100 dynes/cm^2 . Conversely, for a cotton fabric whose surface provides more contacting fibers, the median adhesive strength increases to 250 dynes/cm^2 . Despite the fact that the above values appear to be reasonable and consistent with the dust and fabric properties, the resulting correlations should be accepted only as rough guidelines and not as reliable design parameters. The observed range of adhesive levels over the surface of the fabrics is believed to result from repeated cleaning which leads to a significant spread in adhesive levels, roughly 40 to 200 dynes/cm^2 over about 90 percent of the fabric surface. If this is actually the case, it appears that uniformly distributed unperturbed dust layers should display much higher and more uniform adhesive levels.

For preliminary evaluations, the bench scale testing system, which had been modified previously to permit simulated pulse jet cleaning (Figure 16), was adapted for assessing the relative adhesive characteristics of various coal fly ashes.

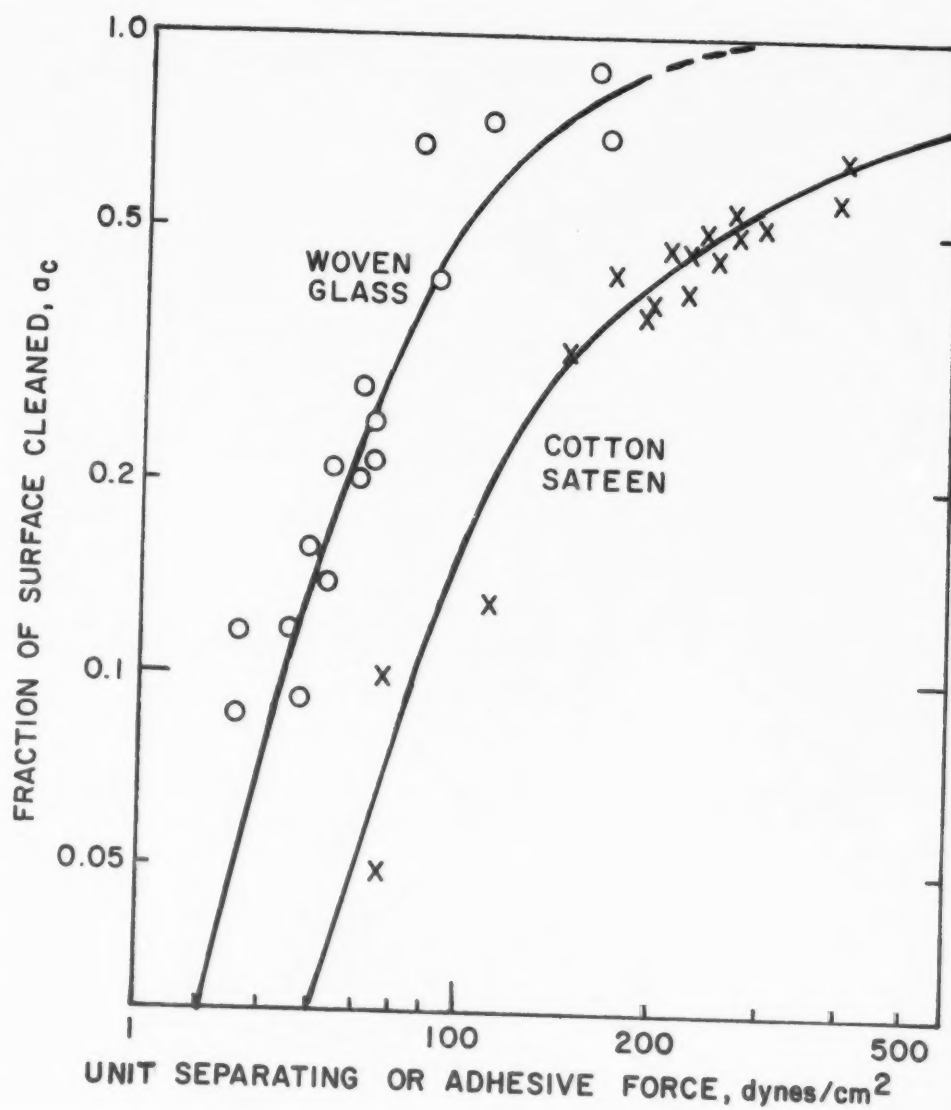


Figure 21. Fly ash fraction removed vs. separation or adhesive force.

TEST RESULTS

Past and present GCA tests,²⁶ as well as those of other investigators,³³ have indicated that 100 percent dislodgement of the surface dust layer is possible (and predicted by theory) provided that: a) sufficient pulse energy is applied and b) no moisture or other absorbable agents cause the dust to bond irreversibly to the fabric. For present test purposes, it was necessary to restrict the pulse energy to levels insufficient for complete cleaning before any relative adhesion criteria could be established. Based upon the fraction of the surface cleaned of the U.S. Steel fly ash (see Table 18), it appears that the pulsing should be carried out at fairly low pressures, i.e., 183 kPa (20 psig) if one is to differentiate between fabric cleanabilities. Although there was not time within this program to compare the several fly ash samples in the simulated pulse jet cleaner, theoretical estimates of cleaning parameters were made based on fly ash particle dimensions and an assumed specific gravity of 2.0. The a_c values shown in Table 19 reflect an average fabric loading of 500 g/m² with cleaning achieved by simple collapse and low-velocity reverse flow. The predicted values are referenced to a measured value of $a_c = 0.1$ for a coal fly ash with a volume diameter (d_v) of 4.17 μm .*

*Public Service Company of New Hampshire, Bow, New Hampshire.

TABLE 18. FRACTIONAL SURFACE CLEANING OF USED DACRON FELT VERSUS PULSE PRESSURE--LABORATORY PANEL TESTS^a

Pulse pressure kPa (psig)	Surface dust loading, g/m ²		Surface fraction cleaned
	Before pulse	After pulse	
183 (20)	467	100	0.79
276 (40)	467	25	0.95

^aU.S. Steel fly ash.

TABLE 19. PREDICTED CLEANING PARAMETERS, a_c , FOR VARIOUS COAL FLY ASHES

Sample number	Fly ash source	Volume ^a diameter d_v , μm	Adjusted ^b fabric loading g/m^2	Predicted ^c a_c
1	Southwestern Public Service, Amarillo, TX	1.06	421	0.05
2	Crisp County, Cordelle, GA	1.42	564	0.13
4	Kramer Station, NPPD Omaha, NE	1.49	592	0.16
6	Texas Utilities, Mt. Pleasant, TX	2.41	955	0.48
7	U.S. Steel, Provo, UT	--	--	--
8a	Amalgamated Sugar "A", Nampa, ID	1.49	592	0.16
8b	Amalgamated Sugar "B", Nampa, ID	0.99	383	0.042
9	Pennsylvania Power & Light Holtwood, PA	2.76	1,100	0.58
12	DuPont, Waynesboro, VA	1.34	532	0.13
13	Westinghouse, Hanford, WA	0.46	183	<0.01
14	Case Medical Center, Cleveland, OH	0.33	135	<0.01
16	Republic Steel, Warren, OH	2.41	956	0.48
17a	Colorado Ute Electric Assoc., Nucla CO, (hopper sample)	0.71	282	0.018
17b	Colorado Ute Electric Assoc., Nucla CO, (bag shakedown)	0.96	397	0.049
18	Public Service Company of New Hampshire, Bow NH	1.26	500	0.1

^aBased on fly ash density of 2 g/cc.^b $W = 500 d_v / 1.26 = 397 d_v$.^c a_c value relative to that for a coal fly ash with a volume diameter of 4.17 μm .

SECTION 7

EXTENSION OF EXISTING MATHEMATICAL MODEL COMPUTER PROGRAM TO INCLUDE PULSE JET CLEANING

PROJECT OBJECTIVES

Previous fabric filter cleaning studies performed by GCA/Technology Division²⁶ and exploratory modeling efforts carried out as a precursor investigation to the present program^{34,35} suggested that there were excellent possibilities for developing predictive models for pulse jet systems. Additionally, the results of research by many investigators³⁶⁻⁴⁵ appeared to confirm many of the concepts set forth by Dennis and Wilder²⁶, as well as providing an independent data base from which various modeling hypotheses could be tested.

It was suspected that the model proposed for filtration systems where cleaning is performed by (a) the collapse-reverse flow approach or (b) mechanical shaking would not apply to pulse jet systems for several reasons. Therefore, although it was intended to make maximum use of the concepts proposed during earlier modeling programs,^{1,2} it was also planned to explore and develop whatever independent means appeared feasible to describe (model) the unique operating characteristics of pulse jet systems. The initial plans for the study called for an intensive review, and hopefully, maximum utilization of existing field and laboratory data with supporting experiments as needed to fill in major data gaps. As the study progressed, however, it became apparent that the primary effort should be directed to the rigorous evaluation of available data from many sources that had never before been assessed as a collective with the object of tying together the results of many independent researchers.

As a result, the modeling concepts presented here are based mainly upon critical evaluations of existing data. By concentrating on the basic model structure, the direction of future research may now be established with assurance that the results will fill in certain data gaps discovered during the course of this study.

BACKGROUND

The pulse jet cleaning concept introduced commercially during the late 1950s^{34,35} is extensively applied, particularly where stability in gas flow rates, space economy, and a capability to handle high dust loadings (up to 25 g/m³) are sought. Despite many successful installations, relatively few

investigators have attempted to describe the cleaning process from a theoretical perspective. Furthermore, the high costs associated with sophisticated instrumentation, along with complex interactions among key variables contributing to the cleaning process, have restricted most functions predicting collector performance to semi-empirical equations. Their proper application usually requires one set of actual performance data for the dust/fabric combination of interest with all relevant design and operating parameters completely specified. The above constraint applies to available models for predicting performance of both single and multi-bag units. Optimum application of pulse jet units has been hampered by certain common misconceptions that still prevail, despite the fact that the experimental findings of several investigators should have long since dispelled them.

For example, a precursor cleaning technique, "Reverse-Jet Cleaning," developed by Hersey and introduced during the early 1950s,^{26,46} relied on a high velocity, 1830 to 2440 m/min (6000 to 8000 ft/min) air jet directed against the clean air (outside) surface of a bag to remove the dust cake. Dust dislodgement by this process is correctly attributed to a combination of aerodynamic forces and fabric flexing at the point of jet impact, the latter effect causing cake fracture and severance of adhesive bonds. What has been ignored by some individuals, however, is the fact that air velocities produced during pulse jet cleaning are at least 100 times smaller than those encountered with the Hersey collectors. Hence, dust removal by air drag alone is relatively unimportant with pulse jet devices.^{26,35,41}

The persistence of false impressions is partly attributable to a failure to publish relevant experimental data in readily accessible journals, as well as to the sparsity of overview documents in which the studies and concepts of various investigators are compared and evaluated. A primary objective of this study is to review various independent studies to determine which concepts relate best to pulse jet collector performance with specific emphasis on the pulse jet cleaning process. Although most field and/or performance tests have concentrated on application problems rather than the theoretical aspects of pulse jet systems, their appraisal has proven helpful in evaluating current filtration and cleaning theories.

COMMON MISUNDERSTANDINGS OF PULSE JET COLLECTOR OPERATION

Proposed Bubble Cleaning Concept

Pulse jet cleaning is still described in some documents, accompanied by imaginative illustrations, as the rapid passage of an air bubble through the bag. During its descent, localized fabric distension is supposed to loosen the dust layer while the transient reverse flow completes the dust dislodgement from the upstream filtering surface. Although there is some truth in the above concept, it overlooks the fact that typical pulse durations of at least 0.06 s far exceed the time for the shock wave to travel to the bottom of conventional felt bags, roughly 0.0036 and 0.01 s, respectively, for 1.22 m and 3.05 m (4 ft and 10 ft) long bags.^{26,35,40} In reality, while the pressure front is advancing, the continued arrival of pulse air at successively increasing rates until the solenoid valve is fully open, maintains the inflating pressure behind the front. Because pulse air entry continues well

after the bottom of the bag is fully pressurized, the concept of an advancing bubble is not consistent with the mechanics of the process which can be inferred analytically and has been confirmed by actual measurements.^{26,35}

Observed Pressure Changes During Pulsing--

If, for analytical purposes, it is assumed that none of the pulse air injected into a bag escapes over the time span required for the solenoid valve to open fully (0.01 s), the time frame for pressure changes at the top and bottom of a 1.22 m (4 ft) bag following pulse initiation can be represented by Figure 22. Variations in bag pressure with distance from the top of the bag and time following pulse initiation are shown in Figure 23. Note that the axial, top to bottom, pressure gradient diminishes when the "full-open" pressure front has reached the bottom of the bag 0.0136 s after valve activation. Simultaneous clean-side pressure profiles determined at two locations for a 1.83 m (6 ft) long felt bag (Figure 24) display the characteristic time lag indicated in Figure 22 over the 0.01 s valve opening period.³⁵ Pressure/time traces for Figures 24 and 25, however, also reveal that once the valve is fully open, the pressure decreases rapidly to a lower and nearly constant level where it remains until the solenoid valve begins to close. Figure 25 depicts more sophisticated pressure measurements on a 1.22 m x 11.4 cm bag under typical filtration conditions.²⁶ The abrupt pressure reduction is attributed to the sudden dislodgement of the surface dust layer that facilitates venting of pulse air in the reverse flow direction. The fact that pressure gradients remain nearly constant (except for the valve opening and closing intervals) also suggests that negligible dust removal takes place once the valve is fully opened.²⁶ It has also been observed that pulse durations as long as 30 s produced no discernible differences in dust removal and/or operating pressure loss across the baghouse.²⁶

Postulated Bag Deformation During Pulsing--

In the preceding discussion, the physical response of the bag to pressure imbalance was not considered except for the erroneous bubble concept. In the following paragraphs, the temporal and spatial aspects of bag deformation are examined for what are considered to be the bounding conditions for bag motion. First, assume that the fabric is infinitely flexible such that any part of the bag will be displaced almost immediately when subjected to a pressure differential. The extent of the displacement or inflation depends on how tightly the bag is fitted to the supporting cage; i.e., the degree of slack available. Additionally, the greater the combined areal density of the bag and its dust loading, the slower will be its response to a pressure change. Hence, very rapid inflation is associated not only with high flexibility, but also a low system mass, as will be discussed later. When the fabric response is nearly instantaneous, the bag contours at selected times following pulse initiation should appear as if they had been generated by thrusting a frustum of an inverted cone into the bag at sonic velocity, Figure 26. The maximum diameter for the hypothetical cone will be approximately the same as that for the fully inflated bag. Maximum lateral displacement at the top of the bag occurs when the valve is fully open (after 0.01 sec). Because of the sonic lag, however, maximum displacement will be seen 0.0136 sec later at the bottom of the bag. The purported bubble effect, Figure 26a, is shown for reference.

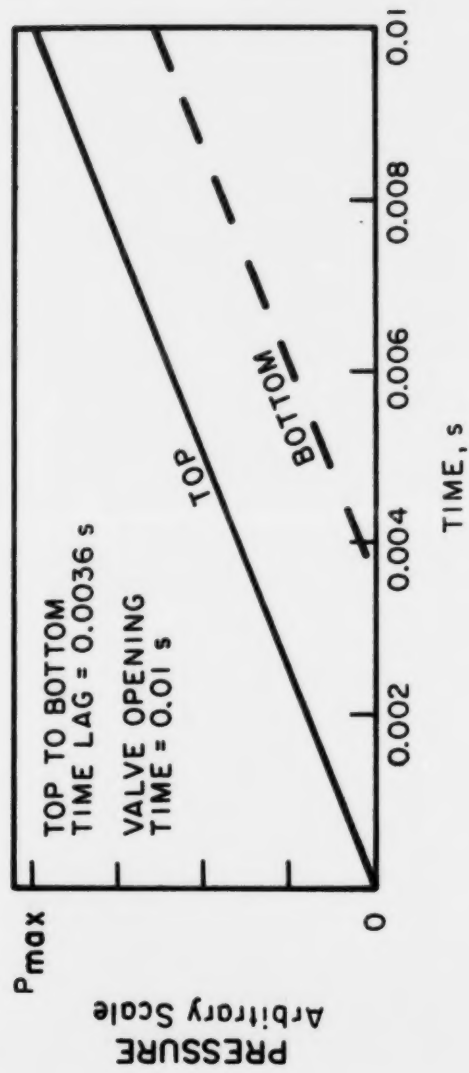


Figure 22. Pressure variation vs. location and time after pulse initiation for 1.22 m (4 ft) long Dacron felt bag.

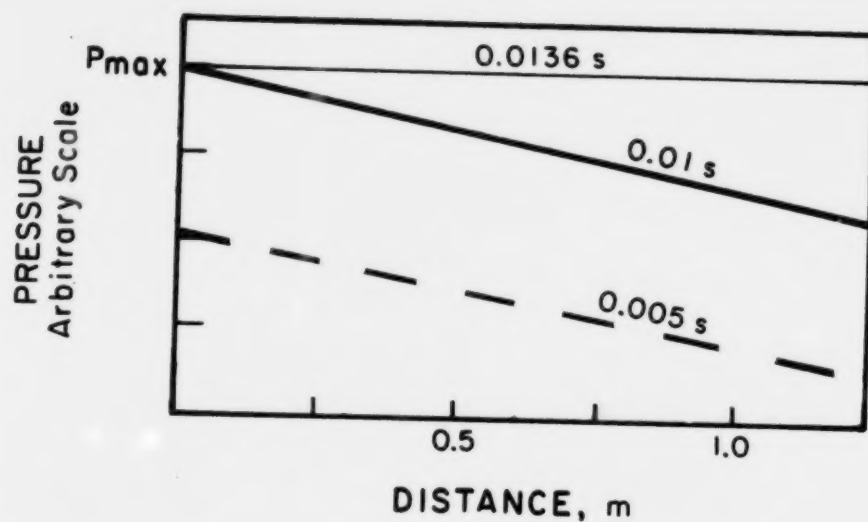


Figure 23. Pressure variations along a 1.22 m long (4 ft) bag vs. solenoid valve open time.

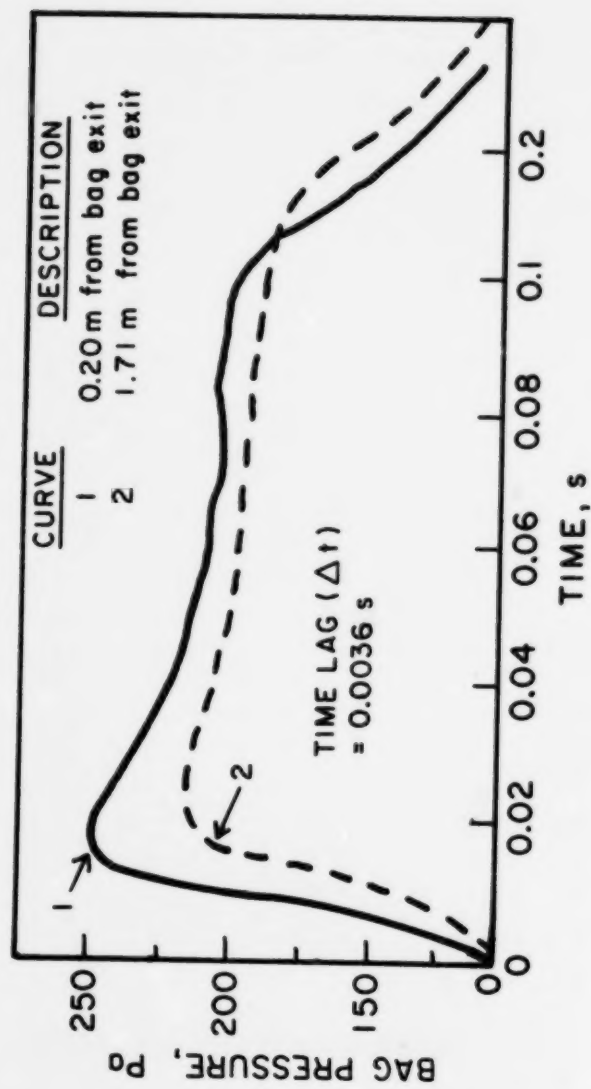
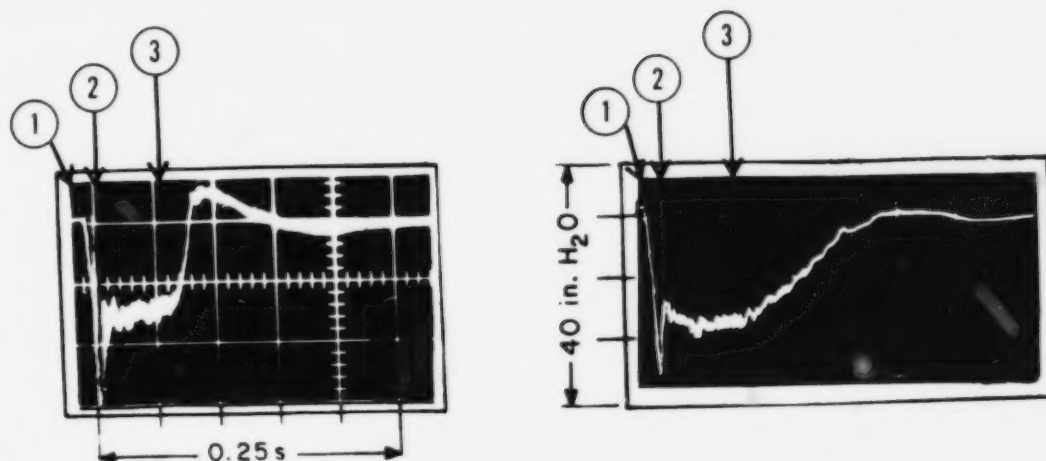
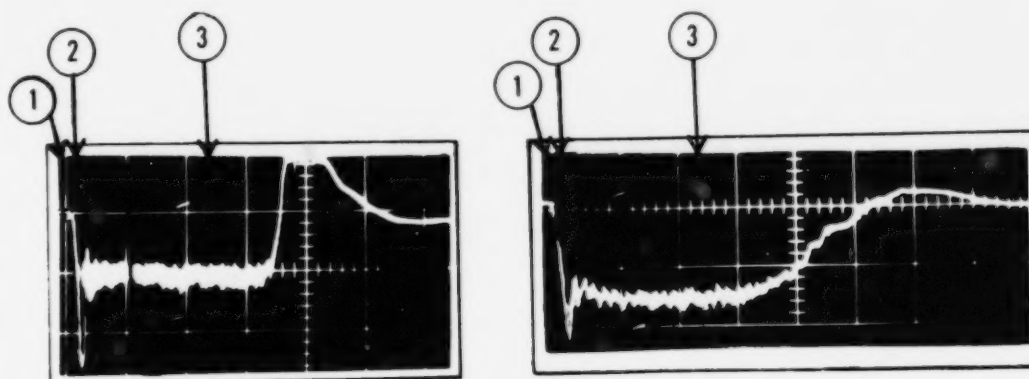


Figure 24. Concurrent pressure/time traces, 1.83 m (nominal 6 ft) long Dacron felt bag for a 621 kPa (90 psig) pulse and 0.1 s duration



0.06s DURATION

- ① INITIATE SOLENOID VALVE OPENING
- ② VALVE FULLY OPEN
- ③ START OF SOLENOID VALVE CLOSING



0.15s DURATION

DIRECT PULSES

DAMPED PULSES

Figure 25. Differential pressure vs. time for Dacron bags 1.22 m x 11.4 cm) (4 ft x 4.5 in.), fly ash filtration, 1 pulse per minute at 483 kPa (70 psig).

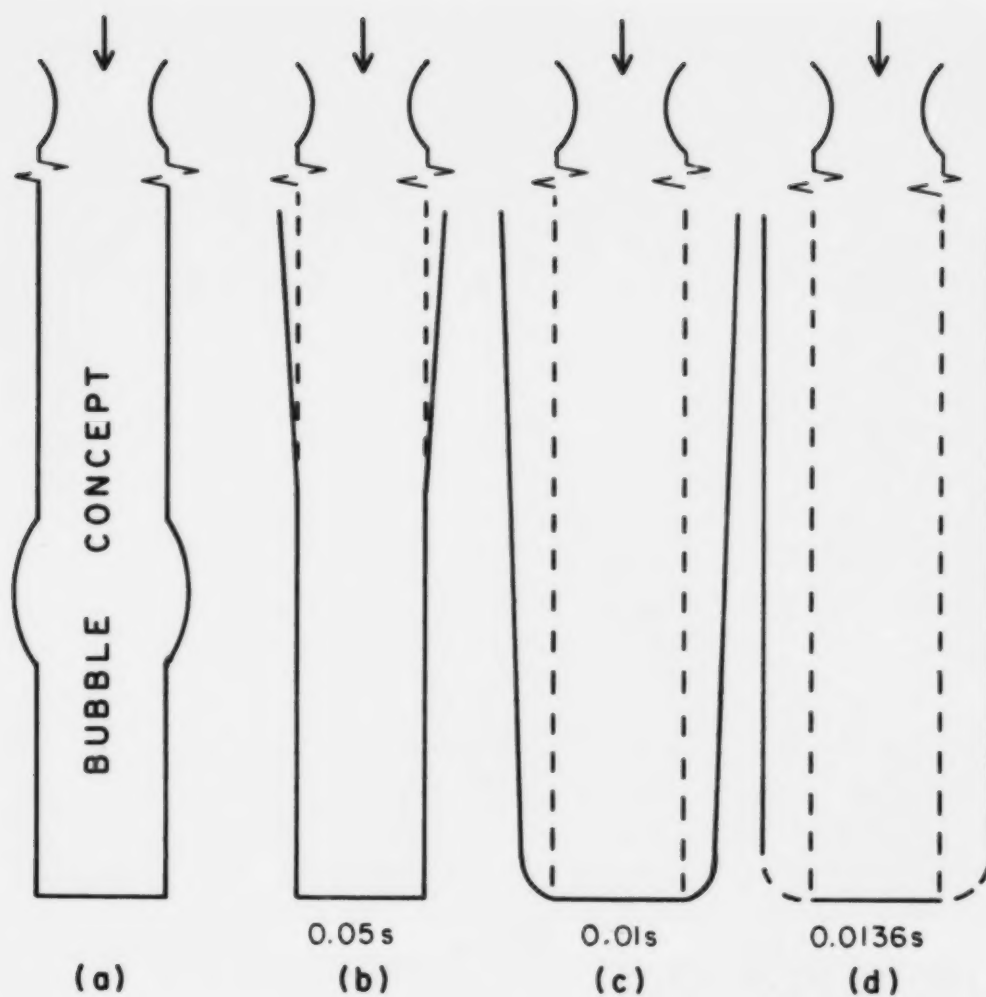


Figure 26. Bag profiles vs. time after pulse initiation for a 1.22 m (4 ft) long bag. Bubble concept (a) vs. theory (b) (c) (d).

Predicted Bag Response to Pulse Pressure--

Under actual filtration conditions, inherent fabric stiffness plus the inertia of the combined dust/fabric mass will cause an appreciable lag in bag response to internal pressurization. The initial radial motion imparted to the dust-laden fabric, as described in earlier studies,^{26,42} consists of a rapid shift or "flip flop" from the normal deflated (filtering) position to its inflated state where the fabric no longer presses against its supporting cage. The approximate lateral (radial) movement can be estimated from the relationships shown below:

$$\rho \frac{d^2 r}{dt^2} + \frac{r}{G} = \Delta p \quad (8)$$

where ρ is the combined dust/fabric mass per unit area, G the flexing parameter, r the radial or lateral displacement, and Δp the pressure acting on the fabric. Further details on the development of Equation (8) are given in this Section under Proposed Modeling Approach.

By equating the restoring force, r/G , that opposes fabric flexure to the opposing acceleration force,

$$\rho \frac{d^2 r}{dt^2} \text{ or } \bar{a},$$

and by treating the lateral displacement or "flip flop" as a simple harmonic motion; i.e.,

$$\bar{a} = 4\pi^2 f^2 r = 4\pi^2 r / \tau^2 \quad (9)$$

the characteristic oscillation period, τ , for a fabric element, may be estimated as $2\pi\sqrt{\rho G}$. Therefore, the time required for the fabric to attain its maximum velocity from a dead start becomes $\tau/4$ or roughly $1.6\sqrt{\rho G}$. When $\tau/4$ is less than or equal to the time required for the pulse to reach its maximum pressure differential (~ 0.01 s), the fabric tends to move with the pulse. Conversely, if $\tau/4$ is much greater than the pulse rise time, a sluggish response should be anticipated with poor cleaning characteristics until the pulse is lengthened. Based on prior determinations of G for wool and Dacron felts,²⁶ $\tau/4$ is expected to range from 0.005 to 0.01 s, thus suggesting a minimal delay in bag inflation for many commercial applications. This study reviews briefly the roles of the flexing parameter, G , gross fabric areal density, ρ , and fabric tensile properties as they apply to fabric cleaning intensity.

Proposed "Depth" Filtration Concept

Cake Versus Depth Filtration--

There are many misconceptions and divergent opinions as to how pulse jet collectors operate. For example, felt filtration is sometimes incorrectly described as "depth" filtration, implying that the fabric functions as a deep-bed filter in which high bed porosity allows the interstitial fibers to play a commanding role in particle capture. Although base line efficiencies

for most felts exceed those for conventional woven fabrics, 90 and 40 percent, respectively, with atmospheric dust,²⁶ it is the surface dust layer and not the felt substrate that is mainly responsible for the high efficiency collection. Except for brief periods, about 0.1 s, when flow direction is reversed by the pulse action, fabric surface loadings fall in the same range, 400 to 1000 g/m²,^{26,41,42} seen for mechanically shaken or reverse-air-cleaned woven fabrics. Therefore, aside from a transient recovery period, primary dust capture should be attributed to sieving by the surface dust layer, whose presence has been well defined photographically.^{26,38}

Some descriptions of pulse jet cleaning also suggest that the maximum surface loading is equal to the amount of dust deposited on the felt during the nominal 1 to 2 minute filtration cycle. If this were so, fabric loadings, W , immediately before cleaning would be expected to range from 2 to 70 g/m² rather than the 400 to 800 g/m² actually determined by experimental measurement.^{26,33,36,38,39} Furthermore, since steady state operation demands equal dust arrival and removal rates, the only dust remaining on the fabric immediately after pulsing must be that imbedded within the felt. Were this the actual case, there would be some justification for the "depth" filtration concept.

Pressure Loss Considerations--

The classical relationship for expressing total pressure loss, P , across a dust-laden fabric; i.e.,

$$P = P_R + P_D = P_R + K_2 V W \quad (10)$$

is often incorrectly applied to pulse jet filter systems. In fact, Equation (10) should only be used when total pressure loss can be divided into two distinct components: P_R , the pressure loss across the fabric per se with or without its residual dust holding, W_R , and P_D , the pressure loss across the surface dust layer. P_D depends upon the specific resistance coefficient for the dust, K_2 ; the filtration velocity, V ; and the areal density, W , for the dust cake. Based upon average values noted for P_R ,

0.1 kPa, the surface dust loadings of 2 to 70 g/m² cited earlier could never be expected to produce the much higher pressure losses observed during typical pulse jet filtration (Figure 27). As discussed later, this problem arises because Equation (10) fails to account for the actual surface loadings of 400 to 800 g/m² that contribute significantly to total system pressure loss. What appears as a rational means to describe mathematically the curves shown in Figure 27 is to introduce an additional component to the right hand side of Equation (10) that accounts for the large quantity, W_c , of the total surface dust loading that is periodically dislodged and redeposited on the felt surface as a bag is repeatedly pulsed. The phenomenon relating to the significance and properties of this "cycling" loading, W_c , is discussed later in Section 7 under Proposed Modeling Approach.

UNIQUE FEATURES OF PULSE JET OPERATION

Dislodgement Forces and Cake Separation

Most investigators agree that the impulse imparted to a fabric, by mechanical shaking or high pressure air pulse, plays a major role in fabric cleaning. Additionally, the degree of cleaning has been related to the

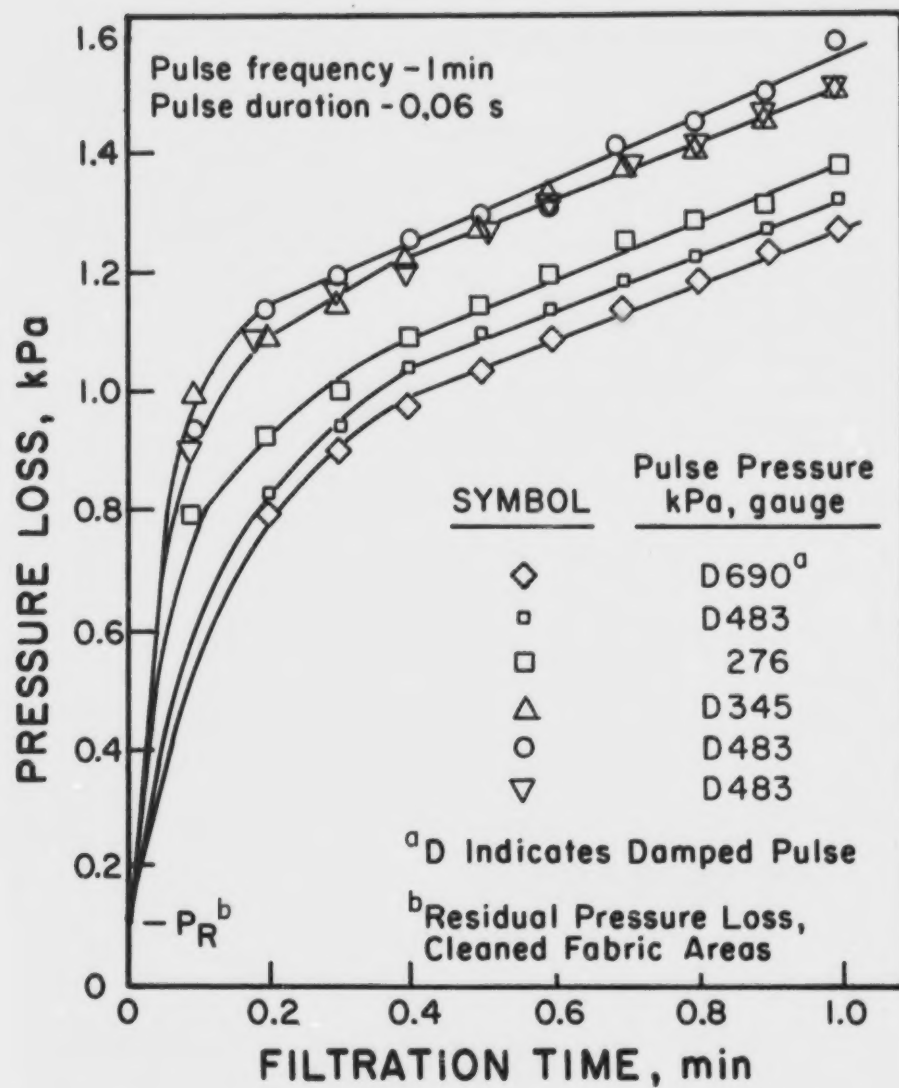


Figure 27. Pressure loss characteristics for fly ash and Dacron felt at $C_1 = 27.6 \text{ g/m}^3$ and $V = 2.6 \text{ m/min}$.

quantity of dust on or within the fabric.⁴⁰⁻⁴² Regardless of fabric type, the dust separating force, F_s , has been defined as the product of the local fabric loading, W , and the maximum deceleration of the supporting fabric beneath it; i.e., $F_s \cong W a_{max}$. Typical a_{max} values have been indicated as 1 g for simple bag collapse systems and 3 to 5 g for mechanically shaken bags.⁴⁰ In the case of pulse jet collectors, however, the combined dust/fabric mass may experience decelerations in the 250 g range, which afford the potential for 100 percent dislodgement of the dust cake as compared to 10 to 50 percent for reverse flow and mechanically cleaned devices.^{26,33,38,42}

Irrespective of cleaning method, dust removal can occur only when F_s exceeds the local adhesive force, F_A , whose magnitude is established by: (a) the unique interfacial bonding properties for a specific dust/fabric combination, and (b) any pre-pulse mechanical disturbance of the dust layer. Additionally, past studies have shown that dust separation occurs principally at the interface between the dust cake and the fabric where the adhesive bonds are considerably weaker than those within the dust cake.^{26,38,42}

Projected Distribution for Adhesive Forces

When a completely cleaned or new fabric is first placed in service, the dust cake and the adhesive forces are expected to be uniformly distributed, barring significant particle fractionation. On the other hand, instantaneous values for separating forces can vary from point to point depending on the method of cleaning and type of fabric support. The first dust to be dislodged is that from areas where local adhesive forces have been exceeded. The fact that only 10 percent removal takes place does not preclude near uniformity for initial adhesion levels because adhesive forces for the uncleaned regions need only exceed the separating forces by a small amount. The "uniformity" concept becomes even more tenable based on the observation that repetitive collapsing, shaking, or pulsing always removes additional dust. Such secondary dislodgement may be attributed to partial severance of adhesive bonds during the first cleaning that decreases adhesion levels over much of the uncleaned surface. After many successive filtration and cleaning cycles, cake adhesion values are expected to embrace a fairly broad force spectrum such as that shown in Figure 21 for a fly ash/cotton fabric system. If it is assumed that the napped cotton surface provides about as many contact points as those for a Dacron felt, and hence approximately the same adhesive properties, extrapolation of the Figure 21 adhesion/force curve suggests that separating forces must exceed 200 N/m² to obtain complete dust cake dislodgement with a single pulse.

The computation of F_s values for pulse jet systems, as indicated below, shows that separating forces well in excess of those essential for complete cake dislodgement, roughly 1000 to 2000 N/m², are attainable.

Fabric Deceleration and Separating Forces

Maximum Projected Dust Dislodgement--

Maximum fabric deceleration, a_{max} , which is imparted to the overlying dust layer, W , determines the separating force exerted at the dust/fabric interface when further bag inflation is prevented by bag tensile properties. Dennis and Wilder have calculated a_{max} from the relationship,^{26,42}

$$a_{\max} = \frac{G}{\sqrt{\rho M_e}} d(\Delta p)/dt \quad (11)$$

Equation (11) indicates that increased flexibility as defined by the parameter, G , causes the fabric to decelerate more rapidly, thereby increasing the magnitude of the dust separating force and the amount of dust removal. Thus, cleaning difficulties may arise if, in attempting to provide a heavier and stronger felt, the penalty of decreased flexibility (or increased stiffness) reduces its initial acceleration capability. Stiffness may also result from dust deposits that increase residual fabric drag, as well as restricting the fabric motion. The increased flexibility for wool felt compared to that for Dacron (Figure 28), may be due to the random dispersion of the fibers in the wool felt. Despite fiber interlockings, the linkages do not favor transmission of localized resistance forces over the length of a bag to the extent possible with the continuous weave of the needled felt scrim. Except for a slightly heavier weight for the Dacron felt (610 g/m² versus 543 g/m² for natural wool) and a small reduction in thickness (0.17 cm versus 0.20 cm) the properties of both fabrics were essentially the same.

Although highly flexible fabrics are desirable during the "flip-flop" or flow reversal phase of the cleaning motion so that the fabric attains its highest possible velocity, minimal elasticity or stretching is required to maximize the final deceleration phase. This observation highlights the fact that the desired attributes of high G and low M_e values may sometimes be mutually exclusive. For example, although natural wool felt demonstrates greater flexibility according to Figure 28, it also exhibits a greater elasticity than fabrics woven from continuous, multifilament yarns. Thus, the initial advantage of a higher velocity during the flow reversal phase (relative to a needled felt) may be offset by a reduction in deceleration due to the increased stretch, M_e , properties of a natural wool felt. With extended service life, most fabrics will exhibit a gradual stiffening, which by itself, suggests reduced cleanability. On the other hand, since M_e values may also decrease (roughly 20 percent for sateen weave cotton and crowfoot weave Dacron),²⁶ the resulting increase in deceleration during the final stopping phase may partially compensate for the adverse stiffening effect. Typical values for the variables appearing in Equation (11) are given in Table 20.

It is emphasized that bag deceleration rates of 125 to 250 g (which should be easily obtainable in routine field applications) coupled with typical fabric dust loadings of 400 to 800 g/m² will generate unit separating forces of 500 to 2000 Pa. Thus, if the surface fiber dispersion for Dacron felts can be approximated by that for a sateen weave cotton (as visual inspection seems to indicate), the force levels should suffice to dislodge completely the surface dust layer.

Conditions Preventing Complete Surface Cleaning--

It is recognized that complete dislodgement of the dust cake may not always be attainable. For example, if the time required to establish a sufficiently heavy dust layer for removal by a fixed set of pulse jet parameters exceeds that for a normal 8-hour shift, complete dust removal, and hence, steady state operation may not be obtained. Additionally, improper jet

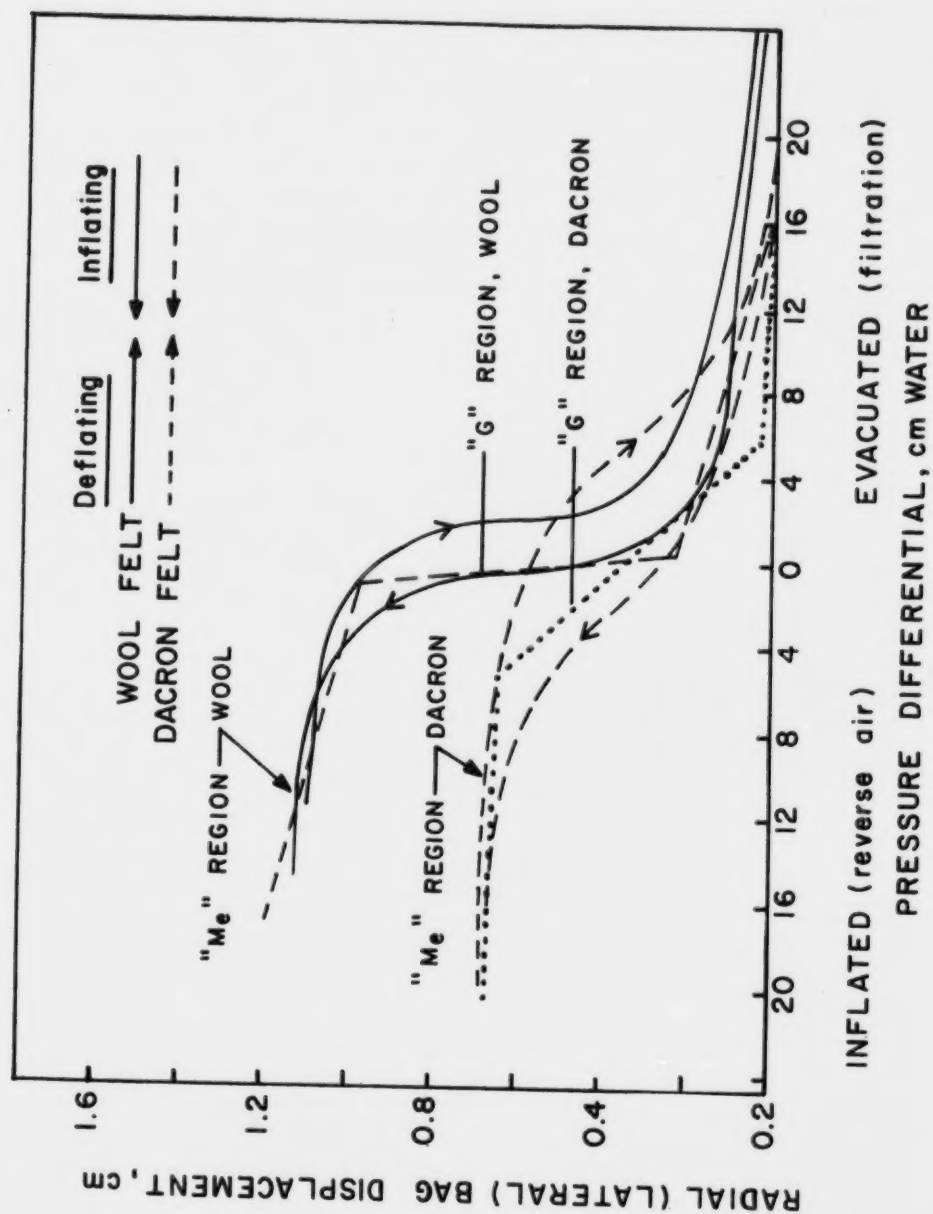


Figure 28. Static displacement of fabric surface at fixed differential pressures with used bags, 1.22 m long x 11.4 cm diameter.

TABLE 20. FABRIC AND PRESSURE PARAMETERS FOR ESTIMATING MAXIMUM
DECELERATION OF A LIGHTWEIGHT, MODERATELY STIFF DACRON FELT

Parameter	Typical values ^a (cgs units)	Definition
G	$5.51 \times 10^{-5} \text{ cm}^2 \cdot \text{s}^2/\text{g}$	Radial displacement per unit pressure
M _e	$2.04 \times 10^{-6} \text{ cm}^2 \cdot \text{s}^2/\text{g}$	Elongation per unit pressure
ρ	$1.26 \times 10^{-1} \text{ g/cm}^2$	Combined dust/fabric areal density
d(Δp)/dt	$2.49 \times 10^6 \text{ g/cm} \cdot \text{s}^3$	Rate of pressure increase
a _{max}	$2.71 \times 10^5 \text{ cm/s}^2$	Maximum dust (or fabric) deceleration

^aNominal values for tests described in Figure 27.

placement may result in secondary air entrainment from the "dirty" side of the bag that can actually increase dust deposition on the upper end of the bag during the pulse interval. In the absence of cleaning, a fraction of the upper fabric surface is lost just as effectively as if the bag were actually shortened. Finally, any dust subject to hydration or other chemical reactions may undergo a cementing action that reduces cake porosity and greatly increases its adherence to the fabric. This problem is accentuated when a filter remains idle in atmospheres where moisture condensation, extraneous reactants, and high temperatures prevail.

Recycled Dust Loading, W_c

The transient character of the flow interruption during pulse jet cleaning, about 0.1 sec, permits only a small fraction of the dislodged dust to reach the hopper. In contrast, practically all dust removed during cleaning processes where compartment flows are interrupted for 0.5 to 2 minutes settles to the hopper or is swept into the inlet ducts of adjoining on-line compartments. It has been estimated that 1 to 5 percent of the dust dislodged actually reaches the hopper,^{26,41,42} and that the remainder is immediately redeposited on the pulsed and/or adjacent bags.^{26,42} Because the dislodged dust consists principally of large, 50 to 100 μ m agglomerates,²⁶ the coarseness restricts redeposition to the surface region, and its specific resistance coefficient has been estimated as five to seven times lower than that for a freshly deposited fly ash.⁴² Low K_2 values for the redeposited or "cycling" layer, W_c , may be inferred from the fact that at steady state operation an average cycling layer of 600 g/m² contributes less than 0.6 kPa to the total pressure loss whereas an overlying, freshly deposited layer of only 60 g/m² causes a 0.4 kPa increase (Figure 6).^{26,42} The precise manner in which W_c contributes to total pressure loss is discussed later.

The term re-entrainment has been used inadvisedly to describe the recycling layer, W_c , as well as referring to hopper dust swept into the air stream when overfilling takes place. Although the latter condition should definitely be eliminated, the true W_c layer plays an important role in the filtration process by providing a barrier that minimizes dust penetration through the relatively inefficient, cleaned fabric. Additionally, it reduces variability in air flow that often cannot be tolerated with many ventilation and process applications. Thus, when adopting off-line cleaning as a means of reducing operating pressure loss, one must also accept the performance penalties of higher emissions and greater flow variability. The preferred method to enhance performance is to select cleaning parameters that enable complete surface dust dislodgement.

Establishment of Steady-State Filtration

Transition from Conditioning to Steady-State Phase--

When pulse jet filtration is initiated either with unused or uniformly cleaned fabrics, the pressure loss increases in accordance with the rate of dust arrival, the filtration velocity, and the K_2 value for the freshly deposited dust. In Figure 29, which simulates the real pressure/time relationships graphed in Figure 27, successive filtering and cleaning cycles

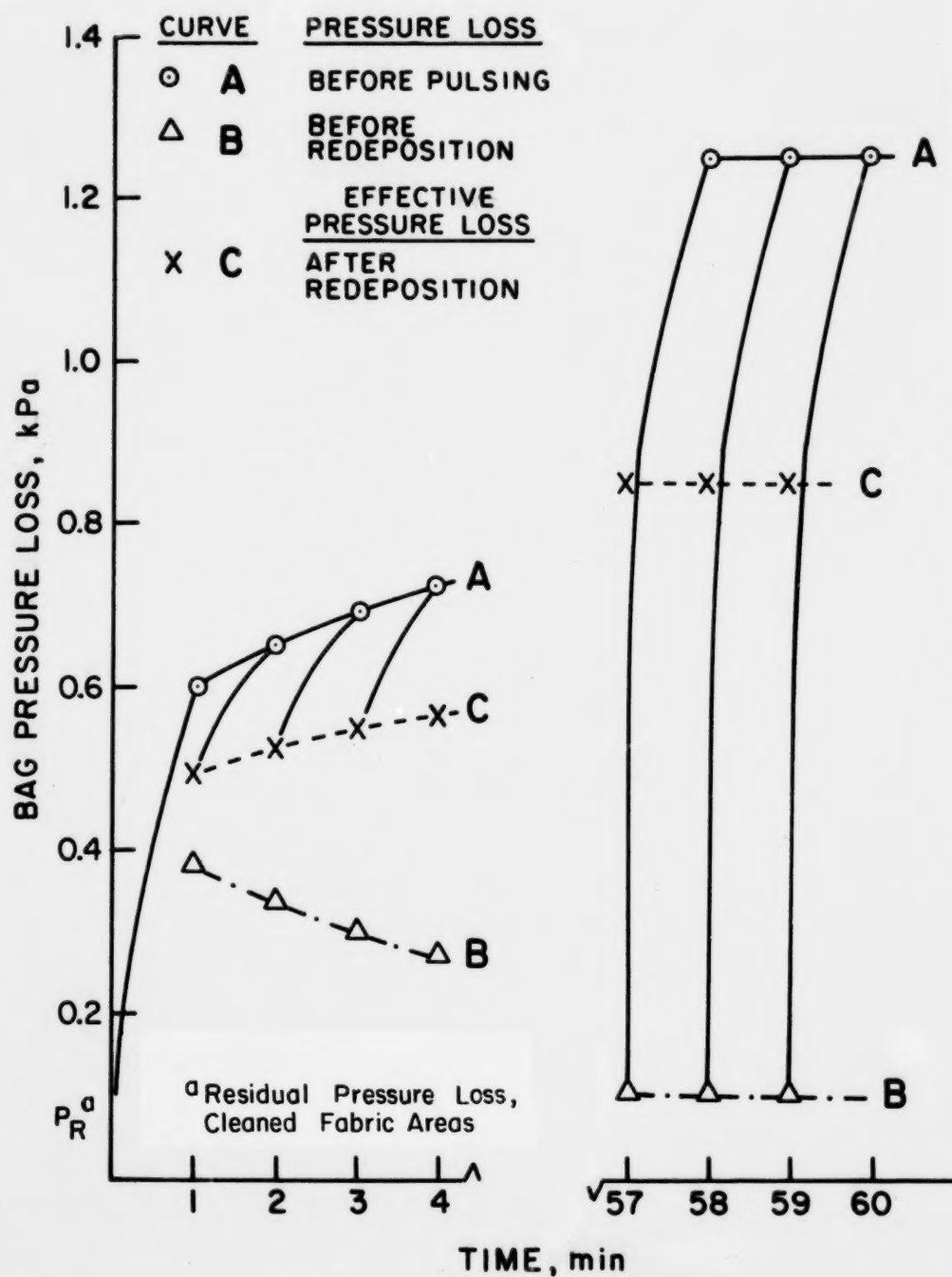


Figure 29. Characteristic pressures before and after steady-state filtration is achieved.

are shown for the first 4 minutes and final 3 minutes of the 60-minute operating period required to reach constant operating pressure (or steady-state filtration). The pressure/time trace for the 60th minute corresponds roughly to the D-690 curve of Figure 27, except for the time scale compression.

At the end of 1-minute, the first pulse dislodges a very small fraction of the initial deposit such that the average (transient) pressure loss arising from unequal flows through the just-cleaned and uncleaned surfaces, respectively, is that designated by the triangles. The almost immediate redeposition, however, of most of the dislodged dust, elevates the pressure to a much higher level depicted by the x symbols, while arrival of fresh dust over the 1-minute filtering period raises the overall filter resistance to an even higher level as shown by the circles. With repetition of filtration-cleaning cycles, the pressure loss before cleaning will reach its maximum value when maximum surface dust removal is attained. In some cases, surface dust removal may not be complete either because of poor nozzle placement or adhesion problems caused by moisture condensation or chemically reactive dusts. After 60-minutes, the transient pressure loss just before redeposition of the cycling load (designated by triangles) must decrease to the base level depicting pressure loss for the uniformly cleaned fabric. Because the interim quantities of dust returned to the fabric must also increase during the conditioning phase, the pressure loss values immediately following redeposition of the cycling load, W_c , also increase until steady-state operation is attained. In Figure 29, the "X" values indicate the pressure that would be obtained if the curves of Figure 27 were extrapolated linearly to zero time. The latter value has been described as the "effective" bag pressure loss, $(P_e)_{\Delta W}$, at the resumption of a filtration cycle in which the newly arriving dust is characterized by the term, ΔW . Its use in predictive modeling is discussed in Section 7 of this report.

Fundamental Pressure Loss Relationships--

In the absence of a recycling layer, W_c , Equation (10) affords a good estimate of total pressure loss based on the respective contributions of the cleaned fabric, P_R , with its residual dust holding and the freshly deposited dust layer, $K_2 V W$. It has been pointed out, however, that the above approach must be modified to account for the very significant contribution of the cycling layer;^{40,42} i.e.,

$$P = P_R + (K_2)_c V W_c + K_2 V W \quad (12)$$

The additional right-hand term depicts the pressure loss across the redeposited or cycling layer in terms of its unique and much lower K_2 value (because of its agglomerate structure) and the filtration velocity, V . Owing to problems in measuring $(K_2)_c$ and W_c , Equation (12) has been reduced to a simpler form for modeling purposes;^{40,42}

$$P = (P_e)_{\Delta W} + K_2 V W \quad (13)$$

where $(P_e)_{\Delta W}$ can be evaluated for a broad range of design, flow, and pulse cleaning parameters. On the premise that there does exist a unique W_c layer that can be described as discussed in the following paragraph and, furthermore,

that complete dislodgement of this layer is possible under optimum cleaning conditions, Equation (13) and its derivatives become important modeling tools.^{40,42}

Steady-State Operating Conditions

Fabric Dust Loadings Versus Dust Concentration and Filtration Velocity--

The basic criterion for 100 percent dust cake removal is that the separating force, F_s , exceed the maximum adhesive force, F_A , the latter uniquely determined by the dust/fabric combination of interest. Therefore, once the pulse characteristics that determine fabric deceleration are fixed, there is a minimum and unique fabric loading, W_c , required for 100 percent cleaning. Variations in inlet dust concentration, C_i , and filtration velocity, V_i , have a negligible impact on W_c as suggested by the loading data shown in Table 21.^{26,40} Bakke's tests, Figure 30, also reflect the independence of fabric loading on inlet concentration.³⁷ For example, with operating pressure loss fixed at 875 Pa, filtration velocities leveled off at nearly constant values irrespective of the broad range in inlet concentrations, 0 to 22 g/m³. Since pressure loss and velocity were constant, it can be inferred that the cycling loading, W_c , must also have been constant. Ellenbecker and Leith have also reported that steady-state or "cycled" dust loadings were essentially independent of filtration velocity over the range 3 to 7.5 m/min.³⁹ Additionally, for comparable operating conditions, their tests revealed not only fabric loadings similar to those reported by Dennis and Wilder^{5,425} and 406 g/m³, respectively, but also relatively uniform dust deposition over nearly the full length of the bags.

Dust Removal Versus Pulse Jet Pressure--

Although we believe that nearly 100 percent dislodgement of the surface dust layer should occur (except for those situations where the jet nozzle is improperly located and/or condensation problems arise), Ellenbecker and Leith have expressed reservations that 100 percent cleaning takes place or that the major cleaning process results mainly from a surface layer release and not some interstitial reorientation of the dust/fiber structure.^{39,41} Iinoya and Mori, however, describe tests on a three bag collector (Figure 31), where pulse pressures ranging from 200 to 700 kPa (29 to 102 psig) resulted in up to 75 percent removal of the total dust holding, 600 g/m², before pulsing.³³ Because no further removal was noted beyond 550 kPa, the surface removal was believed to be essentially complete while the remaining 150 g/m² constituted the interstitial and difficult-to-dislodge residual loading, W_R . Although W_R values for relatively new felts and woven fabrics may be as low as 36 g/m², it is anticipated that gradual plugging after extended service may lead to values in excess of 200 g/m².⁴²

Past and current GCA tests^{26,40,42} also suggest, based on a combination of photographic evidence and fabric weighings before and after pulsing, that 100 percent removal is attainable under the proper operating conditions (see Figure 25 and Table 22). Recent papers by Humphries and Madden⁴⁴ and Klingel and Löffler⁴⁵ also support the concept of complete dust cake detachment under the proper operating regimes. For example, the curvilinear extrapolation of the pressure/time traces of Figure 25 indicates approximate

TABLE 21. EFFECT OF PULSE PRESSURE, INLET CONCENTRATION, AND FILTRATION VELOCITY ON STEADY-STATE (w_c) FABRIC LOADING⁵

Pulse ^a pressure kPa (psig)	Fabric dust loading, g/m ²	
	C = 2.0 g/m ³ V = 2.6 m/min	C = 22.7 g/m ³ V = 1.89 m/min
276 (40)	405	503
483 (70)	366	423

^aPulse duration = 0.06 s; pulse interval = 1 min.

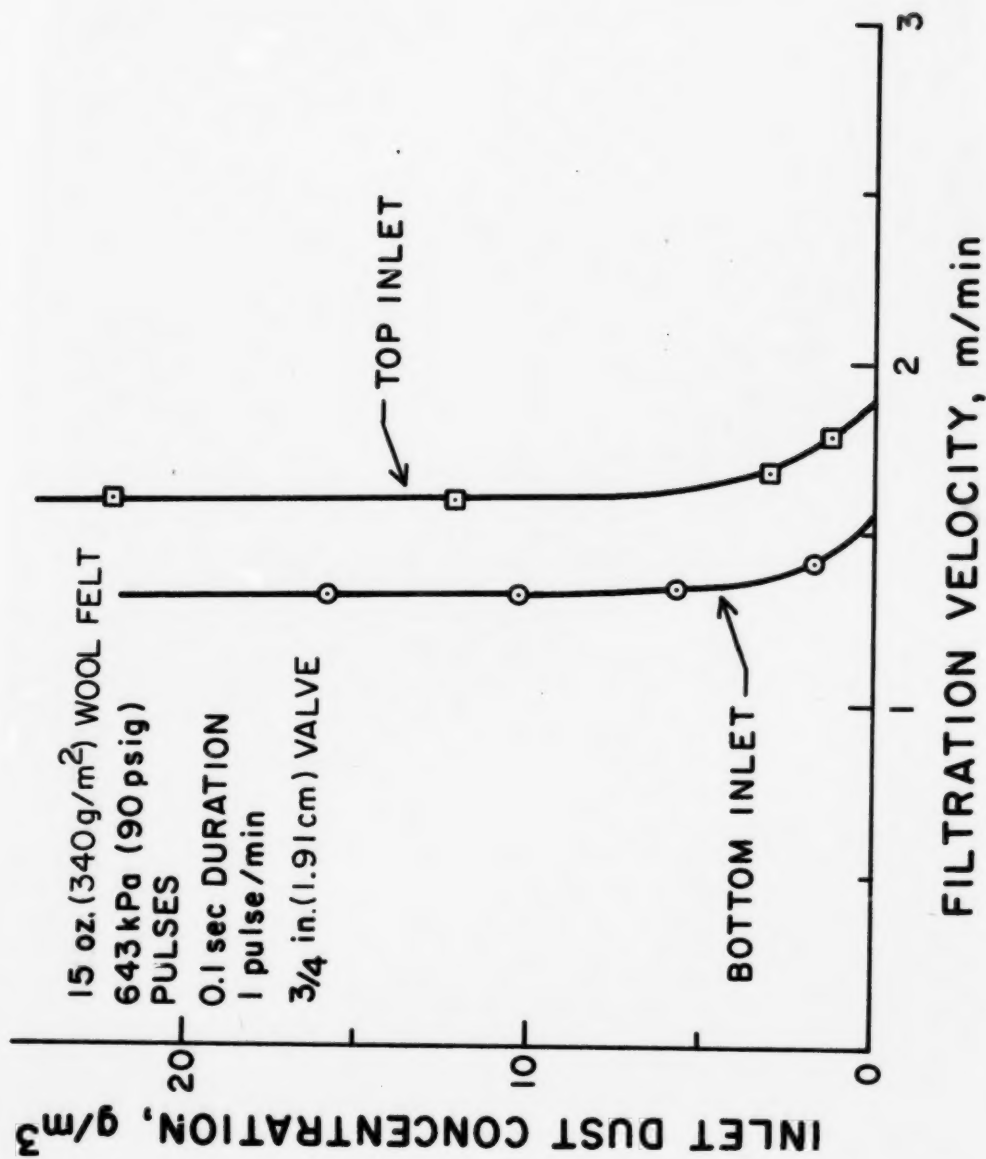


Figure 30. Talc filtration velocity vs. inlet concentration at constant pressure loss.
 Source: Reference 37.

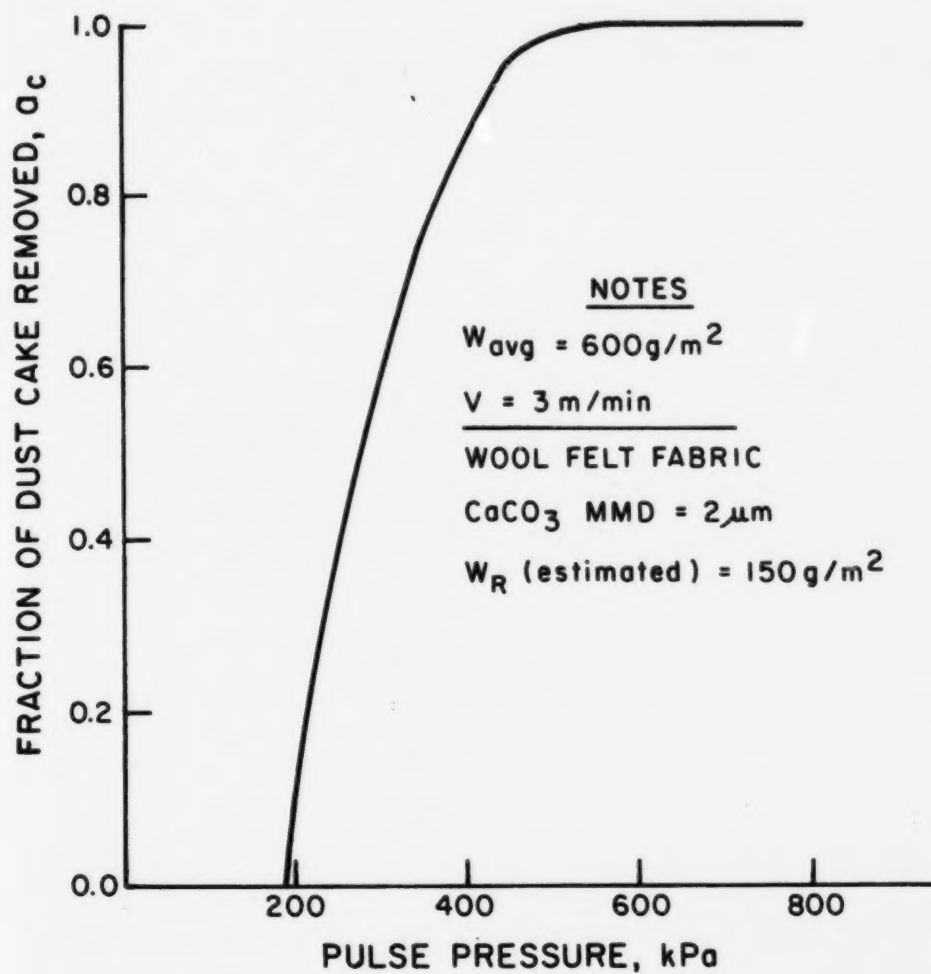


Figure 31. Fractional dust removal vs. pulse jet pressure at constant W .
Source: Reference 33.

TABLE 22. FRACTIONAL SURFACE CLEANING OF USED DACRON FELT
VERSUS PULSE PRESSURE--LABORATORY PANEL TESTS

Pulse pressure N/m ² (psig)	Surface dust loading, g/m ²		Surface fraction cleaned
	Before pulse	After pulse	
183 (20)	467	100	0.79
276 (40)	467	25	0.95

residual pressure losses of 0.1 to 0.2 kPa just before redeposition of the W_c fraction of the dislodged dust. The latter values are consistent with P_R levels displayed by used felts bearing surface dust loadings.

Optimum Performance Criteria--

As indicated in previous studies^{26,40,42}, attainment of optimum operating conditions, which includes 100 percent dislodgement of the surface dust layer, depends upon several pulse-related factors; i.e., pulse pressure and volume relative to bag size, solenoid valve opening time, location of jet relative to bag exit, pulse frequency, and minimum pulse duration.

The effectiveness of the cleaning action also depends on fabric mobility as defined by its flexibility, tensile properties, and inertia, while service life is determined by resistance to corrosion, abrasion, and thermal stresses.

Choice of certain design or operating parameters, such as top versus bottom inlet, air-to-cloth ratio, and (most importantly), conditioning processes plays a key role in obtaining optimum system performance. For example, fabric life can be extended and its residual pressure loss kept at a minimum by avoiding overcleaning and by initiating no pulse action until pressure loss limitations demand it.

PROPOSED MODELING APPROACH

Pressure Loss Factors

Dennis and Klemm⁴⁰ have proposed that the filter drag, S , for a single bag pulse jet unit can be described by the relationship:

$$S = S_E + (K_2)_c W_c + K_2 W \quad (14)$$

where S_E is the residual drag for the used felt with its residual dust loading; $(K_2)_c$, the specific resistance coefficient for the cycling fraction of the total dust loading that is alternately dislodged and redeposited on the fabric; W_c , the cycling portion of the dislodgeable dust loading,⁴⁰ and K_2 , the specific resistance coefficient for the freshly deposited dust fraction, W , that accumulates over the filtration interval, Δt , at inlet concentration, C , and face velocity, V .

Although Equation (14) appears to offer a convenient method for drag estimation, it cannot be applied directly without definition of the $(K_2)_c$ and W_c terms. Therefore, Dennis and Klemm proposed the following restructuring:

$$P = (P_E)_{\Delta W} + 0.001 CK_2 V^2 \Delta t \quad (15)$$

in which filter pressure loss, P , is expressed in pressure rather than drag units and the fabric loading, ΔW , deposited during the filtration interval, Δt , is expressed as $CV t$. The variable, $(P_E)_{\Delta W}$, herein defined as the "effective residual pressure loss," and containing the terms P_E and $(K_2)_c W_c V$, corresponds to the intercept of the linear extrapolation of the pressure-time trace on the pressure axis at the resumption of filtration.

For the experimental pressure curves shown in Figure 32 denoting coal fly ash filtration on needled Dacron felt, the effective residual pressure was related to the compressed air pressure as shown below:

$$(P_E)_{\Delta W} = P_j^{-\beta} \quad (16)$$

where α and β are constants whose values depend upon the type of pulse, direct or damped, and P_j is the compressed air pressure. Equations (15) and (16) constitute useful guidelines for predicting fabric pressure loss for a specific dust-fabric combination, provided that the pulse jet nozzle configuration (including jet diameter and location) and bag dimensions remain unchanged.

Fabric Acceleration--Deceleration Forces

Prior analyses have suggested that a unit separation force of roughly 500 N/m² is required for the complete dislodgement of a coal fly ash surface layer from a Dacron felt.⁴² Laboratory observations have also indicated that the dislodgement of dust from felt fabrics, as well as that from woven glass and cotton, is usually characterized by detachment at the dust layer-fabric interface where the adhesive bonds are weakest.^{31,42} It is recognized that abnormal electrical charge factors, condensation, chemical reactions, and/or very fine particles may affect the manner of dust removal in some field operations. Therefore, if the average fabric loadings, W , are 200 and 500 g/m², respectively, average fabric decelerations, a , of 250 and 100 g are required to achieve complete surface cleaning. Test results for single and multiple bag experimental units have shown total fabric dust loadings, $W_c + W$, to range from 400 to 1000 g/m² with the greater portion distributed uniformly upon the fabric surface.^{26,42} Therefore, any deceleration rate exceeding 125 g would suffice to detach completely the surface layer. Bag "deceleration" is the controlling parameter because it is the rapid slowdown of the dust-laden fabric from its peak radial velocity that produces the tensile stress, or separation force, at the dust-fabric interface:

$$F_s = (W_c + \Delta W)a \quad (10)$$

The descriptors for pulsed bag motion (Table 23) suggest that operation of a single bag filter at simulated field conditions produces deceleration rates ranging from 225 to 296 g depending upon the measurement method.²⁶ In view of the complexity of these measurements, the comparative values for maximum bag displacement from midposition, maximum velocity prior to deceleration, and maximum deceleration show surprisingly good agreement among themselves as well as with the theoretically computed values (Item 5, Table 23).

One-Dimensional Approximation--

During filtration, a typical felt bag drapes inwardly about its supporting cage until the pulse action reverses the pressure differential across it. For the cleaning conditions described in Table 33, the fabric undergoes a total radial displacement of approximately 0.7 cm in moving to its fully inflated position. Experimentally determined static displacements for

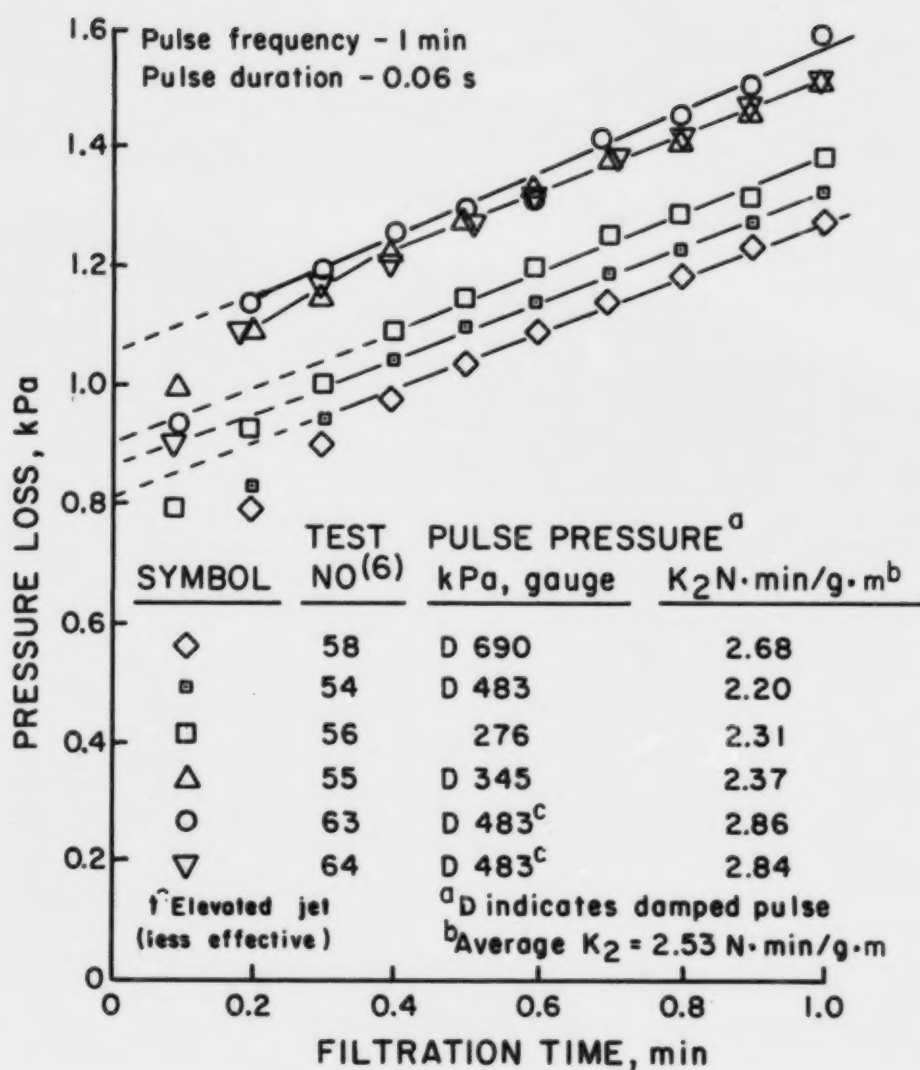


Figure 32. Pressure loss and K_2 values for fly ash with Dacron felt, inlet concentration = 27.6 g/m^3 , filtration velocity = 2.6 m/min . Linear intercept at time zero is effective residual pressure loss, $(P_E)_{\Delta W}$.

TABLE 23. EXPERIMENTALLY DETERMINED DESCRIPTORS OF PULSED BAG MOTION.
DACRON (NEEDED) FELT BAG, 1.22 m LONG, 11.4 cm DIAMETER.²⁶

Measuring procedure	Maximum displacement (cm)	Maximum velocity (cm/s)	Maximum deceleration (g)
1. Static measurements			
Displacement versus pressure	0.66		
2. High speed camera ^{a,b}			
Fabric	0.84	349	296
Dust		192	
3. Strain gauge ^a	0.61	200	272
4. Accelerometer ^a			225
5. Computer values			
Expansion modulus and pressure/ time traces		137 ^c	276 ^d
6. Dust trajectory		61.0	

^aCleaning system--483 kPa (70 psig), 0.06 s pulse (actual time).

^bObserved frequency--133 cps.

^cComputed from Equation 6 (Reference 42).

^dComputed from Equation 8, see Table 11 (Reference 42).

Note: Inlet Concentration (fly ash) ~25 g/m³, filtration velocity = 2.6 m/min.

wool and Dacron felt bags are indicated in Figure 28 as a function of pressure differential. At small pressure differentials, little pressure is required to move the bag in either direction to the extent of its slackness since the pressure need only overcome the frictional stiffness of the filter. After the slackness is removed, fabric tensile properties dominate the motion such that further displacement is minimal. In reversing the pressure differential, hysteresis results because of interstitial friction within the fabric. However, since the cleaning process relates to the outward, inflationary motion, only the lower curve for each bag applies.

The continuous curve may be approximated by two linear branches where, for estimating purposes, the G branch describes the slope in the region where bag flexibility or stiffness is controlling and the M_e branch in the region where elasticity or tensile forces dominate. For dust-laden Dacron bags, the comparative values for the G and M_e parameters, 0.054 cm (radial displacement)/cm water pressure and 0.002 cm (elongation)/cm water pressure, respectively, suggest that resistance to flexure controls most of the radial displacement.

Under these conditions the one-dimensional equation for radial motion can be approximated as follows:²⁶

$$\rho \frac{d^2 r}{dt^2} + \frac{r}{R} = \Delta p \quad (8)$$

where ρ is the mass per unit area for the dust-laden bags, r its radial travel, r/G the resistance force due to bag stiffness, and Δp the instantaneous pressure differential produced by the jet pulse.

Lightweight Fabrics, Motion Controlled by Stiffness--

If the bag motion is governed mainly by its stiffness, (or if radial displacement alone without regard to time is the primary concern), Equation 8 can be approximated by the simpler form, $r/G = \Delta p$. Upon differentiating and rearranging, a useful expression evolves for estimating maximum fabric velocity:

$$dr/dt = V_{\max} = Gd(\Delta p)/dt \quad (18)$$

By assuming linear elastic stretching and negligible friction losses, the bag kinetic energy at midpoint is approximated by the stored elastic energy after the fabric decelerates to its fully expanded state:

$$1/2 \rho V_{\max}^2 = 1/2 M_e (\sigma_{\max})^2 \quad (19)$$

where $\sigma_{\max}$ is defined as the stopping force per unit area.

$$\sigma_{\max} = r_{\max}/M_e \quad (20)$$

Since peak deceleration, $a_{\max}$, can be expressed as $\sigma_{\max}/\rho$, Equations (18), (19) and (20) may be combined to allow estimation of $a_{\max}$ in terms of the following parameters: the density of the dust-laden fabric, ρ ; the stretch and flexing moduli for the fabric, M_e and G ; and the rate of change of pressure differential across the bag during pulsing, $d(\Delta p)/dt$.

$$a_{\max} = \frac{G}{\rho M_e} \cdot d(\Delta p)/dt \quad (11)$$

Equation (11) (which has been called out earlier in this section) provides a means to calculate the separating force, F_s , generated by pulse action in terms of peak fabric deceleration, $a_{\max}$, and the dislodgeable fabric loading, $W_c + \Delta W$. Typical values for the terms appearing in Equation (11) have been given in Table 20.

Despite the simplifying assumptions, use of Equation (11) in conjunction with the operating parameters shown in Table 20 provided an estimate of deceleration rate, $a_{\max}$, that agreed well with measured values shown in Table 23.

Although the terms, G , M_e , and ρ are not difficult to determine with a single bag experimental system, highly specialized equipment involving oscilloscope displays of pressure transducer outputs are necessary to establish the rate of pressure rise, $d(\Delta p)/dt$, within a bag during the pulse interval. Furthermore, even with $a_{\max}$ defined, there still remains the problem of estimating the characteristic cycling dust holding, W_c , for a specific dust-fabric system except by direct weighing or thickness gauge measurements. Therefore, the principal value of Equation (11) at this time is to guide the user in the selection of bag and cleaning parameters.

On the other hand, a strong correlation was demonstrated between the photographically determined $d(\Delta p)/dt$ values (Figure 25) and their corresponding effective residual pressure loss levels $(P_E)\Delta W$, Figure 33. This correlation enabled extension of the modeling capabilities of Equation (15) and (16) to include the effects of nozzle dimensions, solenoid valve opening times, and bag size for the designated reservoir pressure.

Jet Pulse Characteristics

Primary Air Volumes--

Jet pulse characteristics were evaluated over a broad range of operating conditions for a single bag system in which needled Dacron or natural wool felts were pulse cleaned with a conventional commercial nozzle and venturi assembly. Experimental data evaluated here were based on coal fly ash (MMD = $9.2 \mu m$, $\sigma_g = 2.0$) filtration at 2.6 m/min with 1.22 m long by 11.4 cm diameter bags, and inlet concentrations in the 20 to 35 g/m³ range. Pressure regulating valves and pulse durations were adjusted to operate at the reservoir pressure and pulse durations (actual valve open times) indicated in Table 24 with the option to select pulse frequencies ranging from 0.5 to 2 pulses/min. The primary air volumes for 0.06 and 0.15 s pulses as well as the smaller volume ejected from the nozzle during its 0.01 s opening period

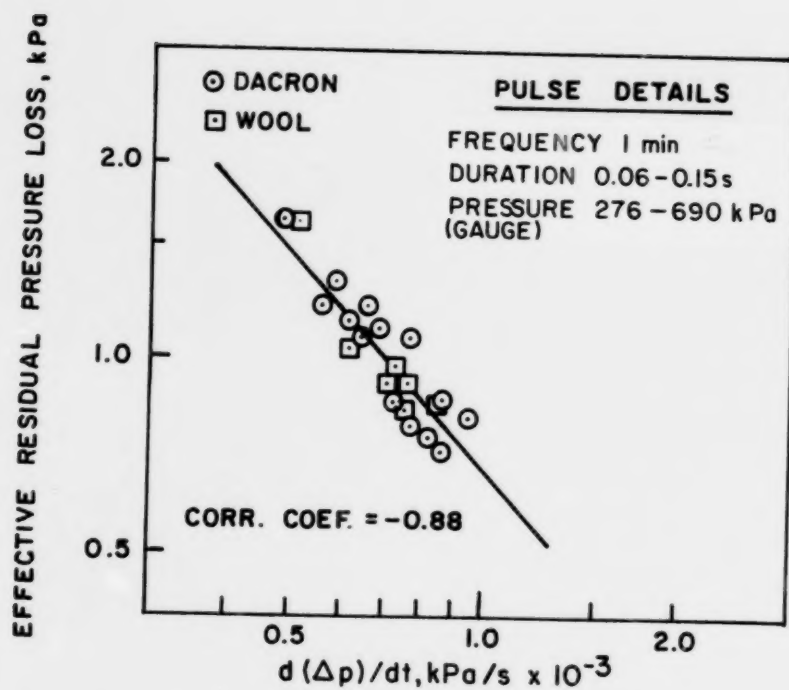


Figure 33. Effective residual pressure loss versus $d(\Delta p)/dt$, 0 to 0.01 s. Fly ash filtration at 2.6 m/min.

TABLE 24. DELIVERED AIR VOLUME (PRIMARY AIR) VS. RESERVOIR PRESSURE, DIRECT PULSES

Reservoir pressure gauge		Measured primary air volume ^a per pulse, m ³ X 10 ³ , STP		
		Valve opening period	Total pulse duration	
kPa	psi	0.01 s ^b	0.06 s	0.15 s
276	40	0.28	3.0	6.0
483	70	0.48	5.4	10.5
621	90	0.68	7.4	13.9
690	100	0.77	8.5	16.2

^aAir for several pulses collected in sounding balloon and transferred to spirometer for metering.

^bVolume assumed to be half that delivered in subsequent fully-open 0.01-s periods.

Note: Standard pulse jet, nominal 1/4-in. nozzle (actually 0.363-in. diameter) and timing controls, Mikro-Pul Division, U.S. Filter Corp., Summit, N.J.

are given in Table 24. The primary air volume should not be confused with the total volume of air pumped into the bag as a result of jet entrainment of secondary air.

Estimation of $d(\Delta p)/dt$ from Pressure-Time Traces--

The oscilloscope traces shown in Figure 25 describe the behavior of short (0.06 s) and long (0.15 s) pulses delivered under normal and damped conditions. As displayed in Figure 25, increasing pressure is read downward as the time scale advances from left to right. Their form follows closely the structure observed previously by Bakke³⁷ and Dennis and Silverman,³⁵ who also used sensitive pressure transducers for tracking rapid pressure changes. The latter measurements³⁵ also showed that the pressure gradients determined at mid bag length were a good representation of conditions over the whole bag. Pressure differentials increase rapidly at first because venting of the pulse air is restricted by the overlying dust layer. It appears that most dust releases when or just before the solenoid valve is fully-open because the pressure decreases suddenly after the first 0.01 s to a lower level that remains nearly constant until the valve is shut. The normal pressure reduction rate is roughly the same as that for the inflation period, whereas a very gradual return results with pulse damping. It was observed that the initial slopes, $d(\Delta p)/dt$, of the pressure-time traces correlated well with the previously discussed effective residual pressure, $(P_E)_{\Delta W}$, as shown in Figure 33, viz;

$$(P_E)_{\Delta W} = 1600(d(\Delta p)/dt) - 1.13 \quad (21)$$

Effect of Cleaning Parameters of $d(\Delta p)/dt$. Equation (21) has no predictive value unless $d(\Delta p)/dt$ can be redefined in terms of readily determined design and operating parameters characterizing the filter system of interest. An analysis of the pulse jet cleaning process suggests that four major variables govern the rate of pressure rise in a pulsed bag: (1) the absolute reservoir pressure, P_{ja} ; (2) the cross sectional area of the delivery nozzle, A_j ; (3) the opening time for the solenoid valve, t_s ; and (4) the volume of the bag itself, V_b . Experimental data (see Table 25), also indicate that $(P_E)_{\Delta W}$ is an approximate linear function of both P_{ja} and the maximum static pressure observed on the clean air side of the bag, P_{max} ; i.e.,

$$d(\Delta p)/dt \propto (P_{ja}) \quad (22a)$$

$$d(\Delta p)/dt \propto P_{max} \quad (22b)$$

The volume of primary air, V_p , delivered during the solenoid valve opening period can be estimated by the following expression.

$$V_p = (M/\rho_b)(t_s/2) \quad (23)$$

where M is the nozzle mass flow rate, ρ_b the primary air density reduced to bag conditions, and $t_s/2$ is the effective opening time for the solenoid valve. It was assumed that the effective mass flow rate, M , during the opening interval was roughly half that of the fully-open state. Because the ratios of bag static pressure before cleaning, P_b , to the reservoir

TABLE 25. VARIATION OF MAXIMUM CLEANSIDE BAG PRESSURE AND $d(\Delta p)/dt$ WITH RESERVOIR PRESSURE. FLY ASH FILTRATION AT 2.7 M/MIN, 1.22 M X 11.4 CM BAG.

Reservoir pressure			$d(\Delta p)/dt$		Maximum clean-side bag pressure	
Absolute	Gauge		kPa/s		kPa	
kPa	kPa	psi	Dacron ^a	Wool ^a	Dacron ^a	Wool ^a
377	276	40	527 $\pm$ 72	503 $\pm$ 70	7.28 $\pm$ 0.85	8.97 $\pm$ 0.94
584	483	70	680 $\pm$ 82	723 $\pm$ 84	9.12 $\pm$ 0.94	9.90 $\pm$ 0.98
794	693	100	925 $\pm$ 95	922 $\pm$ 95	13.5 $\pm$ 1.14	12.5 $\pm$ 1.11

^aEstimated means and standard deviations.

pressure, P_{ja} , is usually less than the critical level, r_c , of 0.53 where sonic velocities obtain, i.e. $P_b/P_{ja} < 1/0.53$, mass flow can be calculated by the compressible flow relationship,⁴⁷

$$M = 40.4 C_d P_{ja} A_j / \sqrt{T_{ja}} \text{ (g/s)} \quad (24)$$

in which C_d is the coefficient of discharge (dimensionless and assumed to be unity) P_{ja} the compressed air reservoir pressure in kPa, A_j the jet nozzle cross section in m^2 , and T_{ja} the reservoir air temperature in $^{\circ}K$, where the subscript a designates absolute values for compressed air temperature and pressure.

Although the combined roles of the jet nozzle (or orifice) and the venturi element at the bag exit have been correctly described as a jet pump system,³⁷ the analysis of its performance during the initiation of the pulse places the entire entrainment process in the nonsteady state realm. Hence, the classical, semi-empirical relationships between pressure ratios and the ratios for primary and secondary air flow rates do not apply. For estimating purposes, it was assumed that during the solenoid valve opening time of 0.01 s, primary and secondary air were ejected into the bag with no permeation through the dust-laden bag and no reverse (180°) venting from the bag.

The average pressure observed within the bag during the inflation process reflects the air volume contributed by the primary flow plus the secondary volume, V_s , resulting from momentum transfer to the surrounding air from the sonic velocity jet. At the completion of the filling process, assuming that no air has vented from the bag, the instantaneous bag pressure will have been increased from its original base level during filtration, P_b , by the factor $(V_p + V_s)/(V_b + V_p + V_s)$. When the bag volume far exceeds the air volume injected by the pulse, the rate of pressure increase $d(p)/dt$ may be defined by the approximate expression.

$$d(\Delta p)/dt = \left(\frac{V_p + V_s}{V_b} \right) \left(\frac{P_b}{t_s} \right) \quad (25)$$

Although V_s is not readily determined, it may be inferred from Equations (23) through (25) that $(V_p + V_s)$ should also be directly proportional to V_p ; i.e., $V_p + V_s = kV_p$. Strictly speaking, Equation (25) describes the rate of pressure increase on the downstream (clean) side of the bag and not the pressure differential across the bag that causes the bag motion. However, because dirty side pressures are ordinarily very small compared to their clean side counterparts, Equation (25) constitutes a good approximation of $d(\Delta p)/dt$ as may be inferred from Equation (22).

By combining and rearranging Equations (23) through (25), $d(\Delta p)/dt$ can be expressed as follows:

$$d(\Delta p)/dt = (k20.2 P_{ja} A_j / \sqrt{T_{ja}}) (P_b / V_b \rho_b) \quad (26)$$

where P_b is the absolute pressure on the clean side of the bag in kPa, V_b the bag volume in m^3 , and ρ_b the ambient (bag) air density in kg/m^3 . A value of 2.12 was computed for the constant k , based upon the data presented

in Table 25 and the physical units used in Equation (26). If filtration is performed at sea level conditions where values of 21.1°C (70°F), 101.6 kPa (14.7 psia), and 1.2 kg/m³ (0.075 lb/ft³) may be assumed for T_{ja}, P_b, and ρ_b, respectively, Equation (26) may be reduced to the simple form

$$d(\Delta p)/dt = 211P_{ja}A_j/V_b \quad (28)$$

Since the parameter (P_E)_{ΔW} can be determined by a process of combination and substitution with Equations (15), (16), (26) and (27), the pressure loss for a single bag unit can now be estimated from Equation (15); i.e.,

$$P = (P_E)_{\Delta W} + 0.001CK_2V^2\Delta t \quad (15)$$

Given only one pressure loss vs. time (or fabric loading) curve such as those shown in Figure 32, the filter designer or user can estimate bag pressure loss for any set of operating conditions that may include variations in inlet dust concentration, filtration velocity, frequency of cleaning, intensity of cleaning as defined by reservoir compressed air pressure, compressed air orifice dimensions and valve opening time, bag volume, and the temperature, barometric pressure, and density of the filtered air. All predictions, however, apply only to the dust-fabric combination described in the single test.

If no data such as given in Figure 32 are available, the predictive equations are only useful when the dust-fabric combination of interest possesses the approximate dust dislodgement or adhesive properties of the coal fly ash-Dacron felt system used to develop Figure 32 and Equation (13). For example, prior measurements with a more readily dislodged talc dust have shown that the constant (1600) in Equation (13) should reduce to approximately 630.26.⁴⁰ Thus, estimates of effective residual pressure levels would err on the high side by about 0.5 kPa (2 in water) if fly ash data were applied.

Pressure Loss - Multi-bag Units

The modeling equations described above may be extended to typical multibag, sequentially-pulsed field units by iteration processes similar to those used with reverse air or mechanically shaken systems.^{40,48}

$$\bar{S} = \left(\sum_{i=1}^{n_b} \frac{a_i}{S_i} \right)^{-1} A \quad (29)$$

where S is the average system drag, n_b is the total number of bags, A is the total cloth area, a_i = A/n_b and S_i ranges from S = (P_E)_{ΔW}/V to S = (P_E)_{ΔW}/V + 0.001CK₂VΔt.

A rough estimate of average system drag for a multibag system is also obtained by introducing the coefficient 0.75 into the right hand member of Equation (15) that designates the drag increase attributable to the freshly deposited loading:

$$S = (P_E)_{\Delta W}/V + 0.00075 C K_2 V \Delta t \quad (30)$$

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APPENDIX A

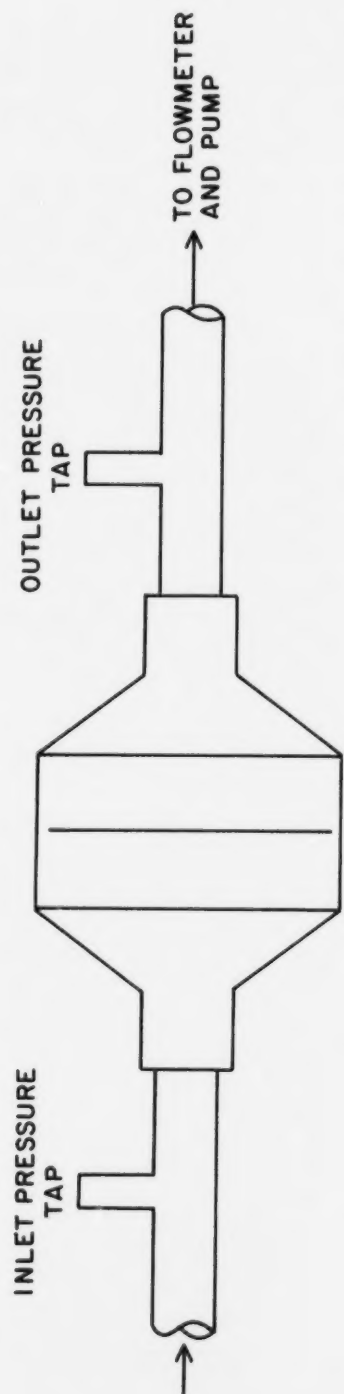
PROPOSED TECHNIQUE FOR FIELD DETERMINATION OF THE SPECIFIC RESISTANCE COEFFICIENT, K_2

Under ideal test conditions, the determination of K_2 should be made at the same gas velocities, temperatures, and inlet loadings found in the baghouse and the dust should be collected on the same fabric used in the actual filter system. It is expected that once steady state combustion (load level) is attained, the gas temperatures and flow rates will be nearly constant in the filter system at the point where gas sampling must be performed. Although particulate concentrations should, in theory, also be constant, field measurements have shown that fluctuations may occur due to random variations in coal ash content. Thus, to account for any variability in inlet loading, the special sampling system for estimation of K_2 should allow for short term measurements of mass concentration.

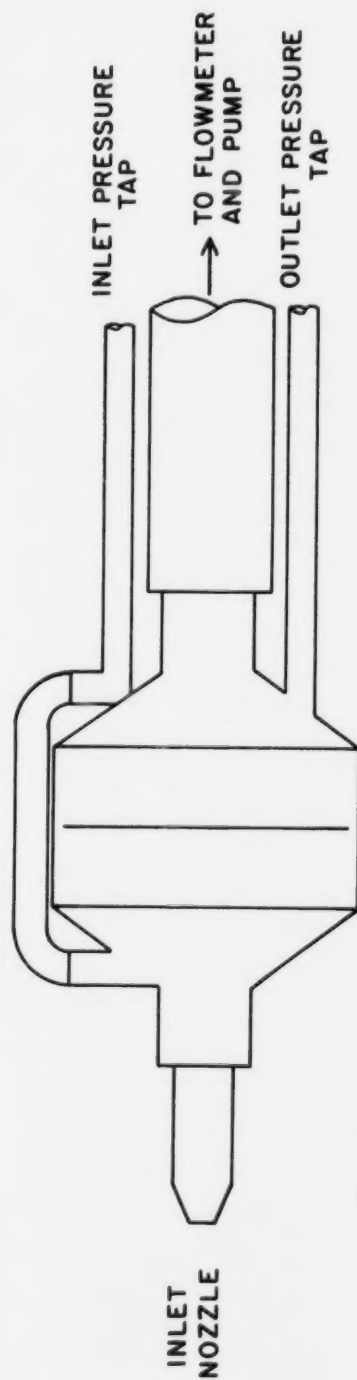
A practical method for the field measurement of K_2 has evolved from test procedures developed during studies relating coal properties to fly ash filterability. Even during controlled laboratory testing, problems in pressure regulation of dust feeders sometimes cause undesired variation in inlet dust loadings. Because of loading variations, the slope of the drag curve with respect to time no longer is constant even after the pore filling phase is complete. Therefore, the true curve slope under constant loading conditions cannot be determined unless several (4 to 5) successive filter weighings are made over the course of the test. Although permissible in the laboratory, it would be very impractical to assemble and disassemble the field apparatus for several weighings. It has been found, however, that if the dust is collected on a very planar surface, e.g. a membrane filter or even a conventional Method 5 glass filter, the substrate filter and dust layer both display their unique permeabilities. Thus, when a uniform dust concentration approaches the filter face, the path of the drag-loading curves is linear and any deviations from linearity reflect either a change in inlet concentration and/or filtration velocity.

With a constant filtration velocity, it is only necessary to determine the initial and final pressure losses across the filter and the total amount of dust collected over the measurement period (one weighing only). The above procedure is expected to work except for the unusual situation where the dust layer is highly compressible (which does not apply to most fly ashes at fabric loadings $<1000 \text{ g/m}^2$).

Conventional, filter holders supporting 5 cm diameter all-glass filter circles provided with inlet and outlet pressure taps are the key elements of the proposed field assembly. If a 4 inch sampling port is provided, which is not unreasonable for most field installations, the filter holder can be placed within the duct at the location of interest while its connecting probe leads to an exterior pump and flow metering system. A major advantage of this arrangement is that line loss problems are eliminated just as they are with Method 17 sampling. However, unless the dust samples are collected at system locations that typify the size properties of the dust actually reaching the fabric, corrections must be made. Figure A-1 shows schematically the nozzle design proposed for K_2 determinations.



A. Filter Holder - actual laboratory assembly



B. Filter Holder - proposed field assembly

Figure A-1. Test apparatus for K_2 determination schematic, with 47-mm membrane filter circles.

APPENDIX B
FLY ASH SIZE PARAMETERS

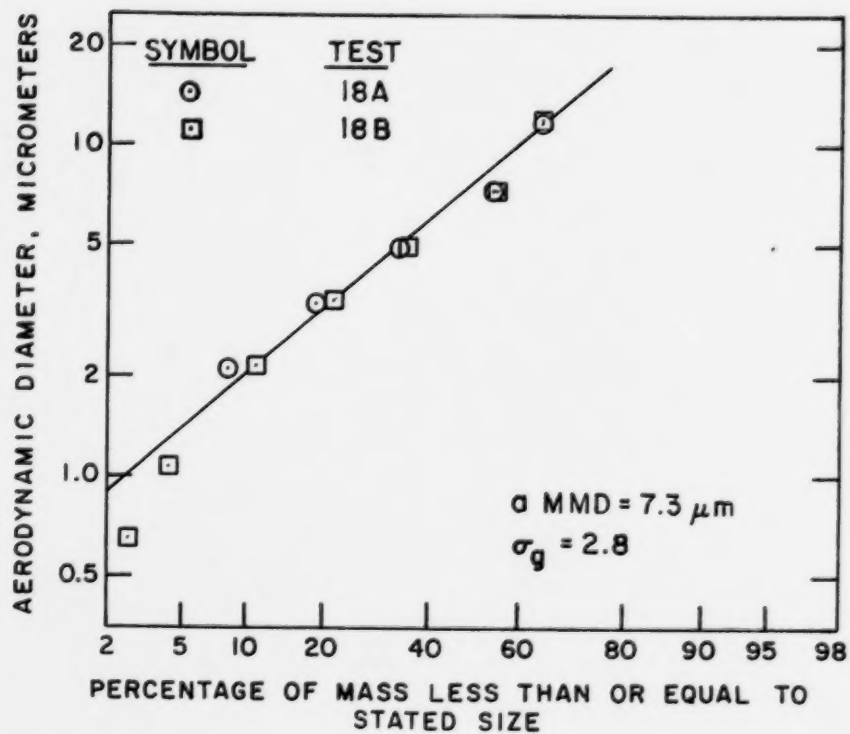


Figure B-1. Particle size distribution for Southwestern Public Service resuspended fly ash, Andersen Mark III impactor measurements. Sample 1.

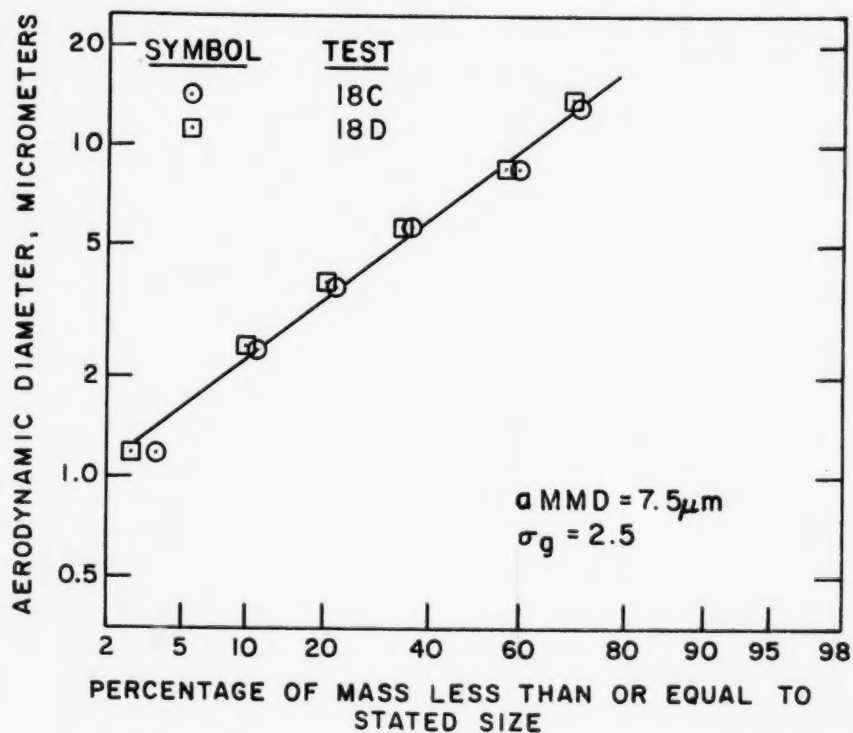


Figure B-2. Particle size distribution for Crisp County Power Commission resuspended fly ash, Andersen Mark III impactor measurements. Sample 2.

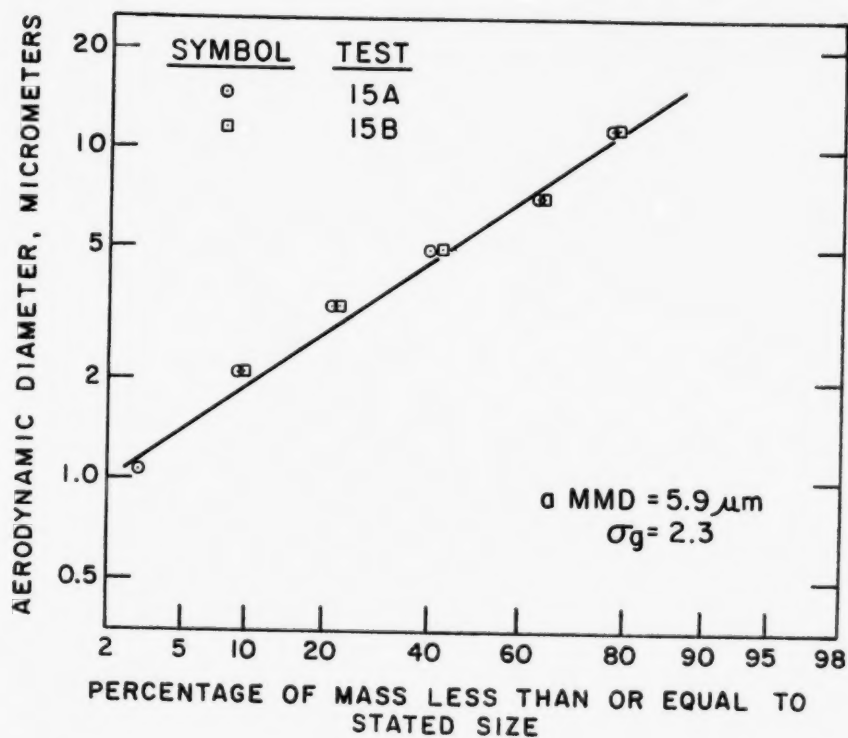


Figure B-3. Particle size distribution for Kramer Station resuspended fly ash, Andersen Mark III impactor measurements. Sample 4.

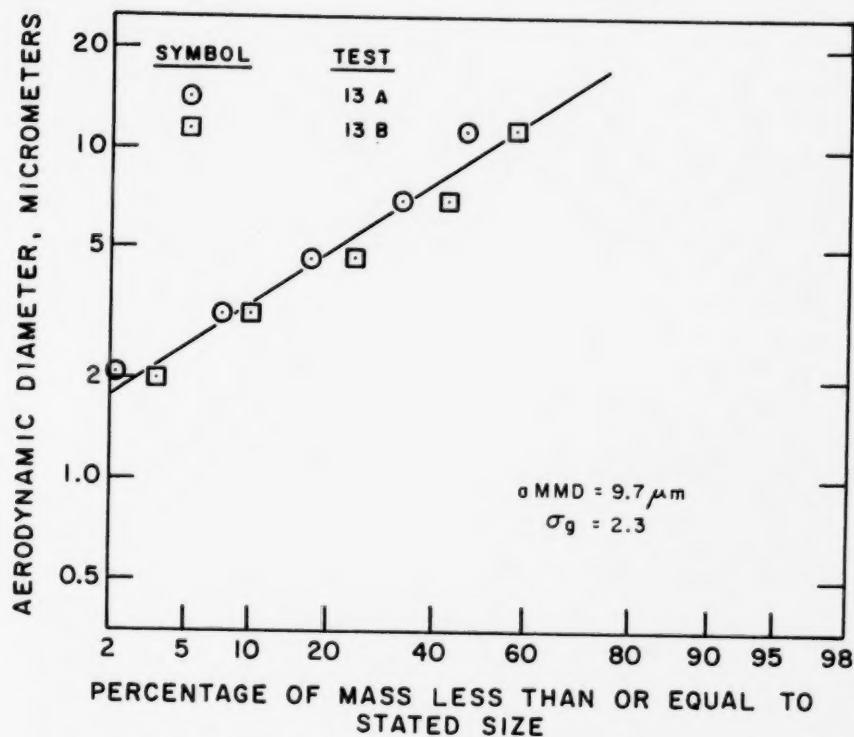


Figure B-4. Particle size distribution for Texas Utilities resuspended fly ash, Andersen Mark III impactor measurements. Sample 6.

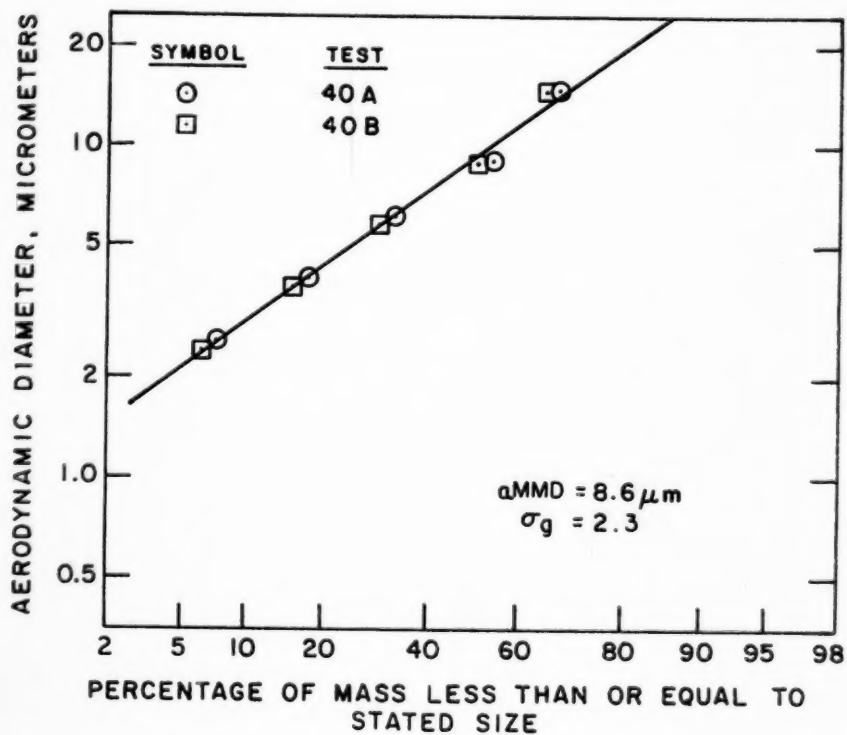


Figure B-5. Particle size distribution for U.S. Steel, Provo, Utah resuspended fly ash; Andersen Mark III impactor measurements. Sample 7.

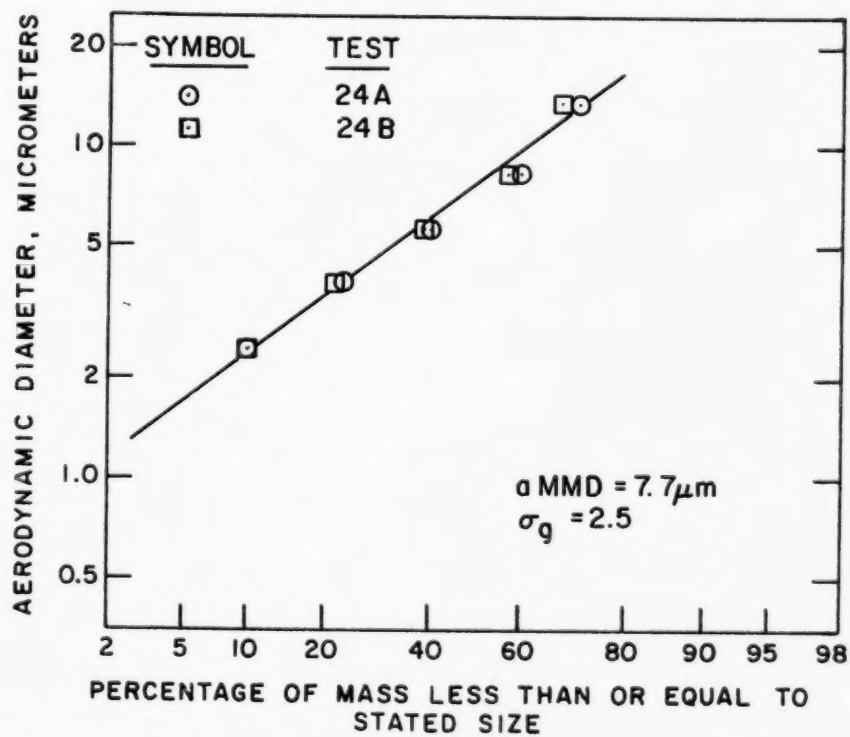


Figure B-6. Particle size distribution for Amalgamated Sugar Sample A resuspended fly ash, Andersen Mark III impactor measurements. Sample 8A.

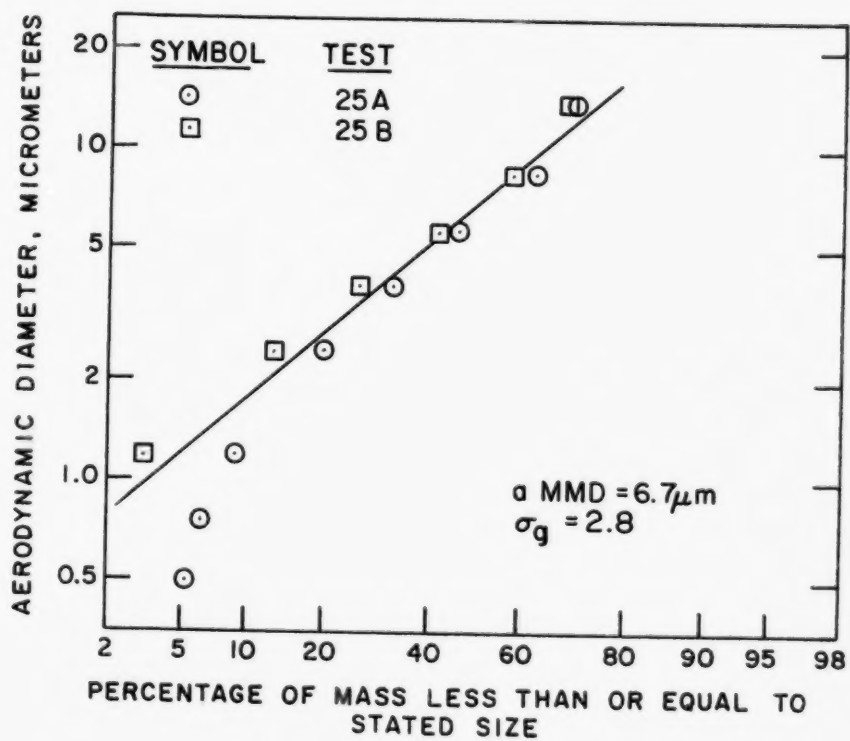


Figure B-7. Particle size distribution for Amalgamated Sugar--Sample B resuspended fly ash, Andersen Mark III impactor measurements. Sample 8B.

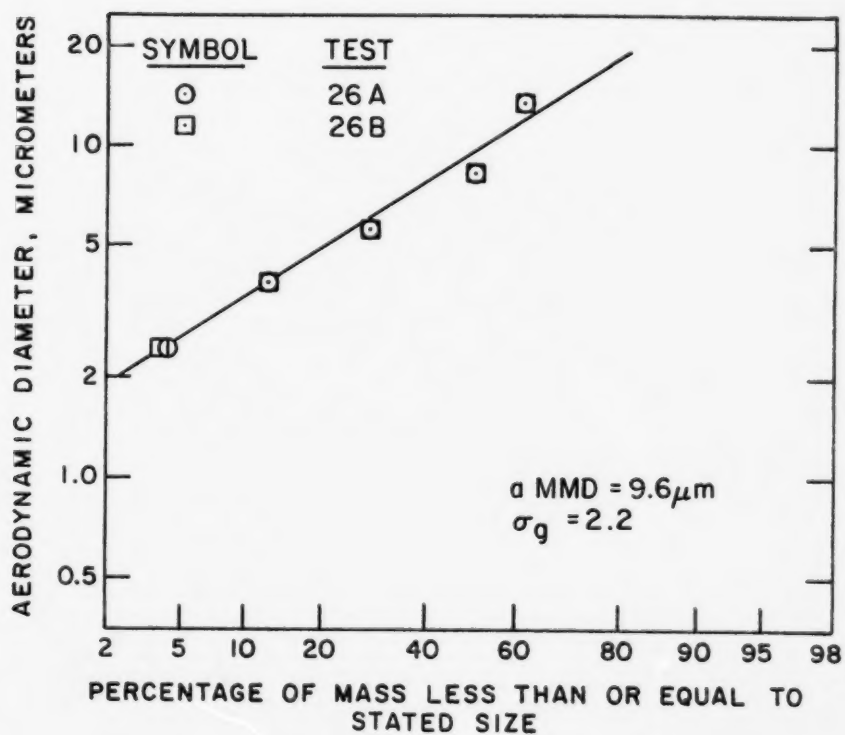


Figure B-8. Particle size distribution for Pennsylvania Power & Light, Holtwood Station resuspended fly ash, Andersen Mark III impactor measurements. Sample 9.

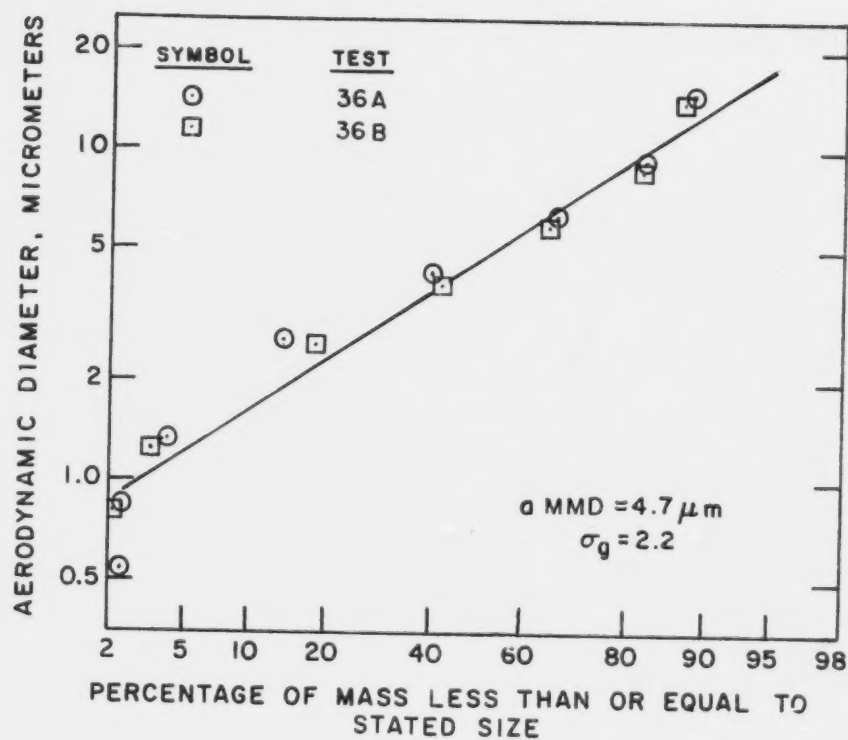


Figure B-9. Particle size distribution for Dupont's Waynesboro plant resuspended fly ash, Andersen Mark III impactor measurements. Sample 12.

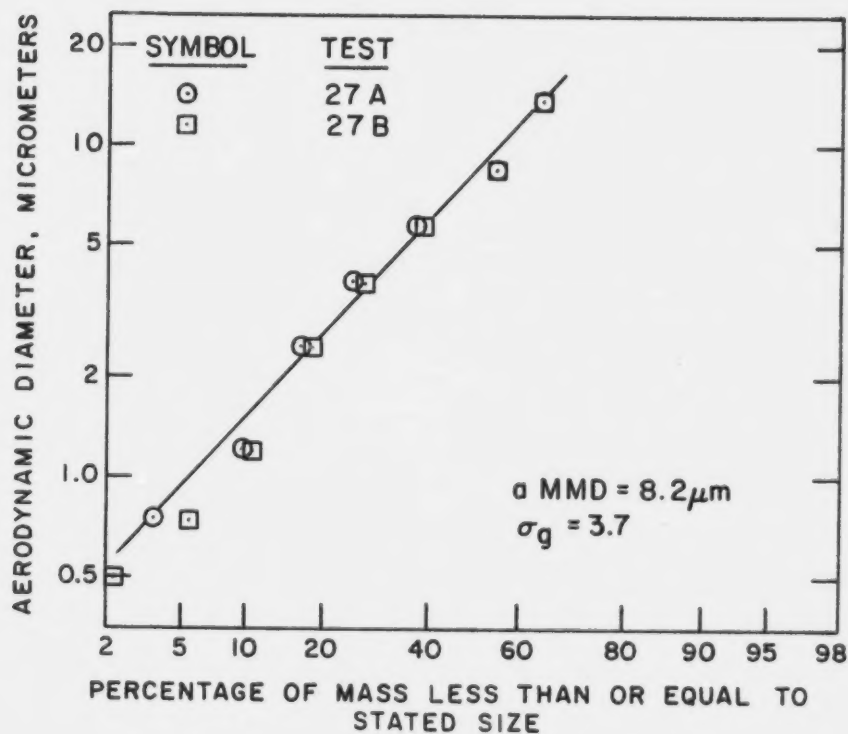


Figure B-10. Particle size distribution for Westinghouse Hanford, resuspended fly ash, Andersen Mark III impactor measurements. Sample 13.

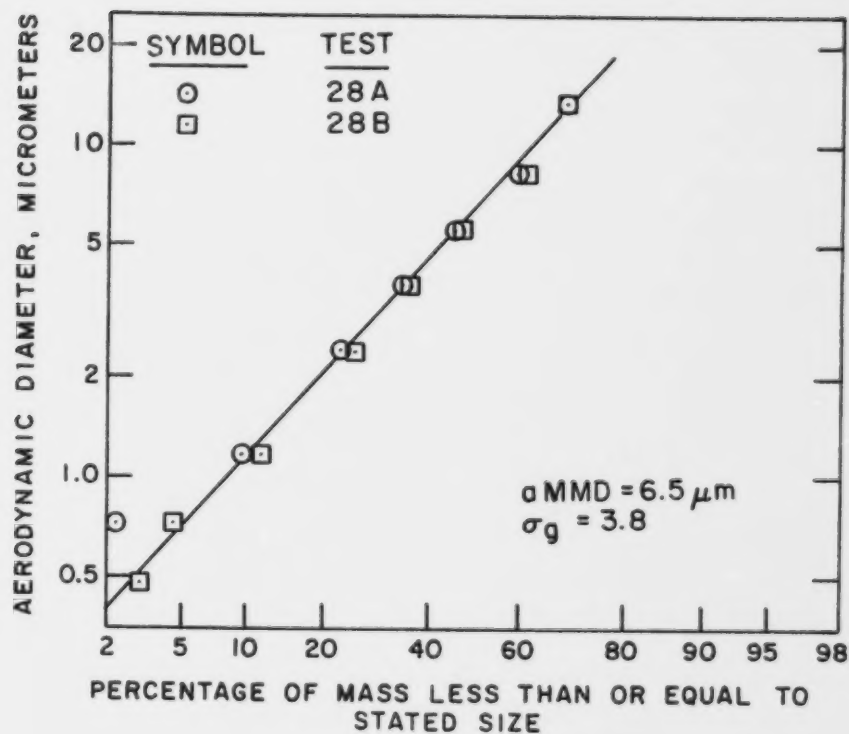


Figure B-11. Particle size distribution for the Case Medical Center resuspended fly ash, Andersen Mark III impactor measurements. Sample 14.

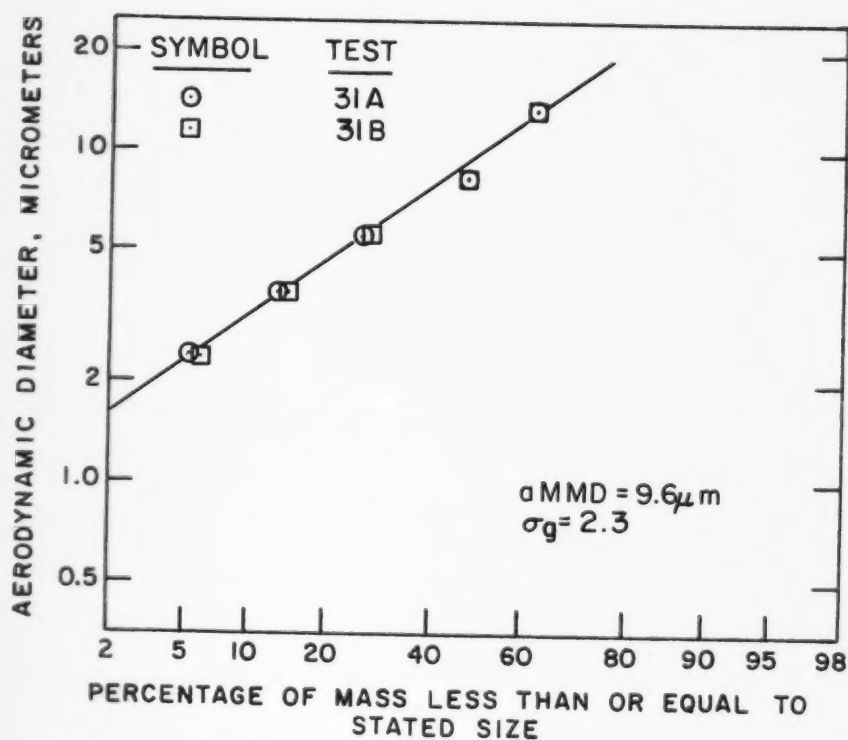


Figure B-12. Particle size distribution for Republic Steel resuspended fly ash, Andersen Mark III impactor measurements. Sample 16.

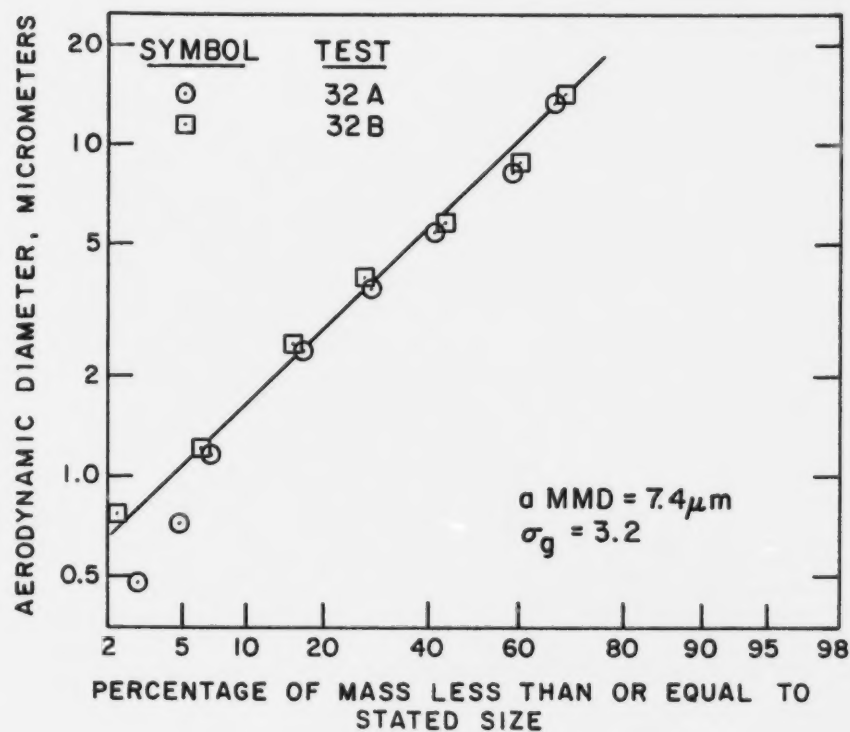


Figure B-13. Particle size distribution for Colorado-Ute Electric Association Nucla Station--Hopper Sample resuspended fly ash, Andersen Mark III impactor measurements. Sample 17A.

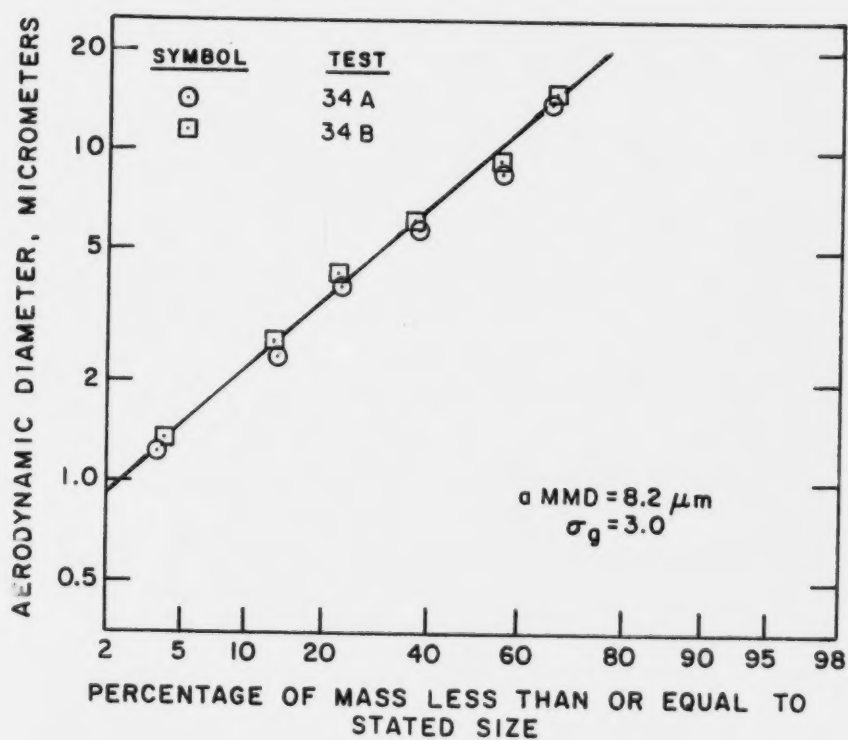


Figure B-14. Particle size distribution for Colorado-Ute Electric Association Nucla Station - Shake Down Sample resuspended fly ash, Andersen Mark III impactor measurements. Sample 17B.

APPENDIX C

DRAG VS. FABRIC LOADING CURVES
FOR TEST FLY ASHES

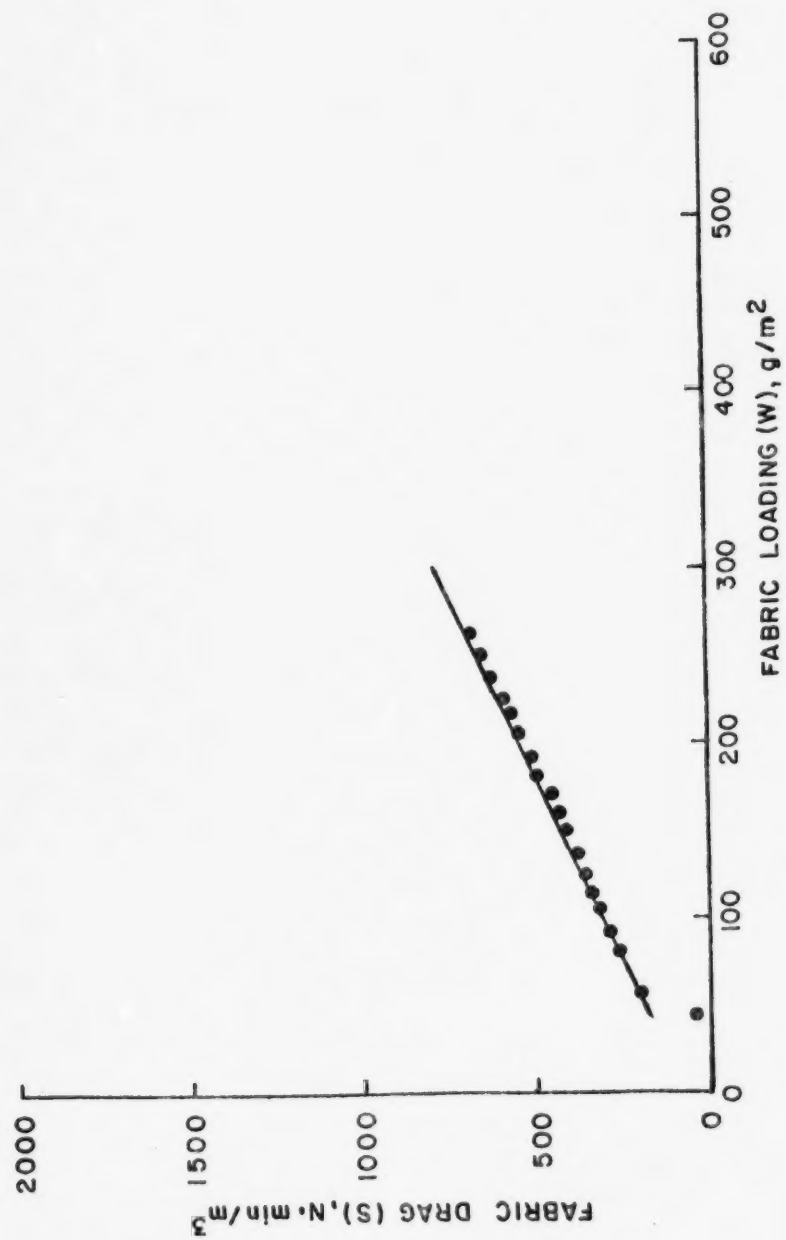


Figure C-1. Drag vs. fabric loading, Southwestern Public Service. $A/C = 0.61$ m/min.

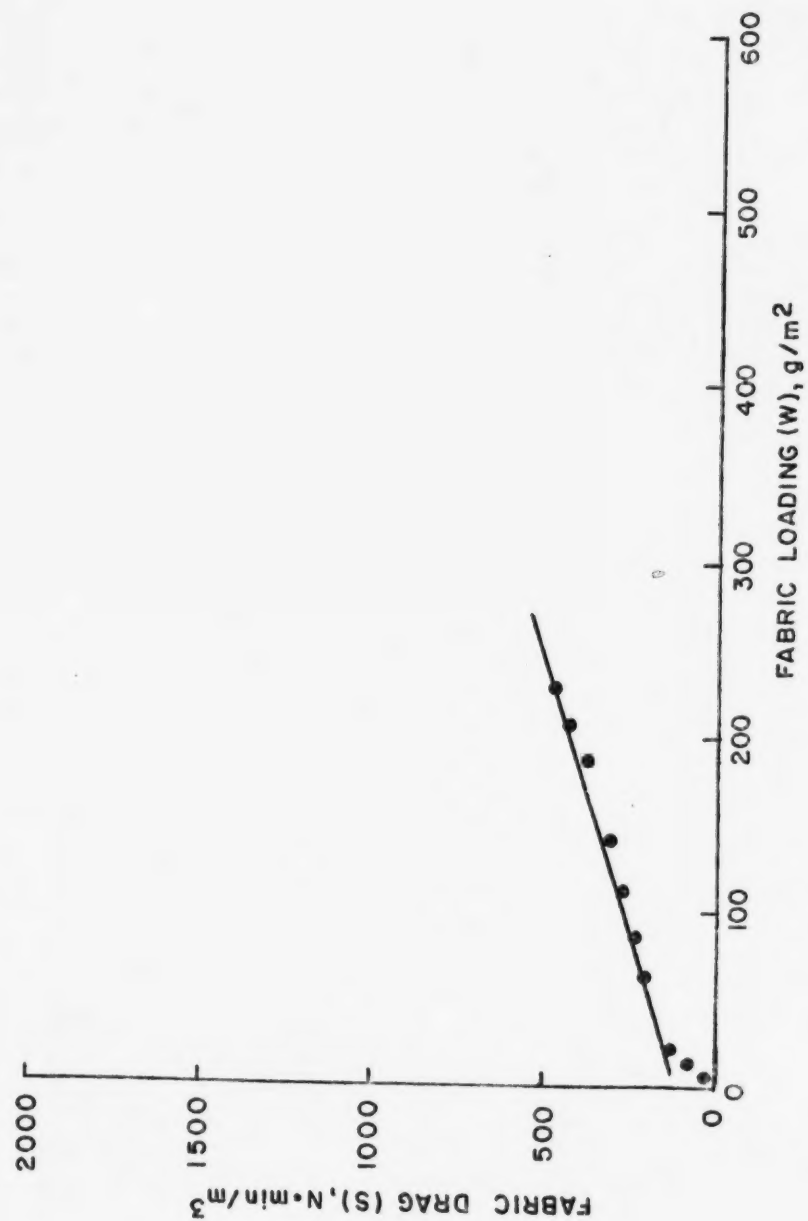


Figure C-2. Drag vs. fabric loading, Crisp County. $A/C = 0.61$ m/min.

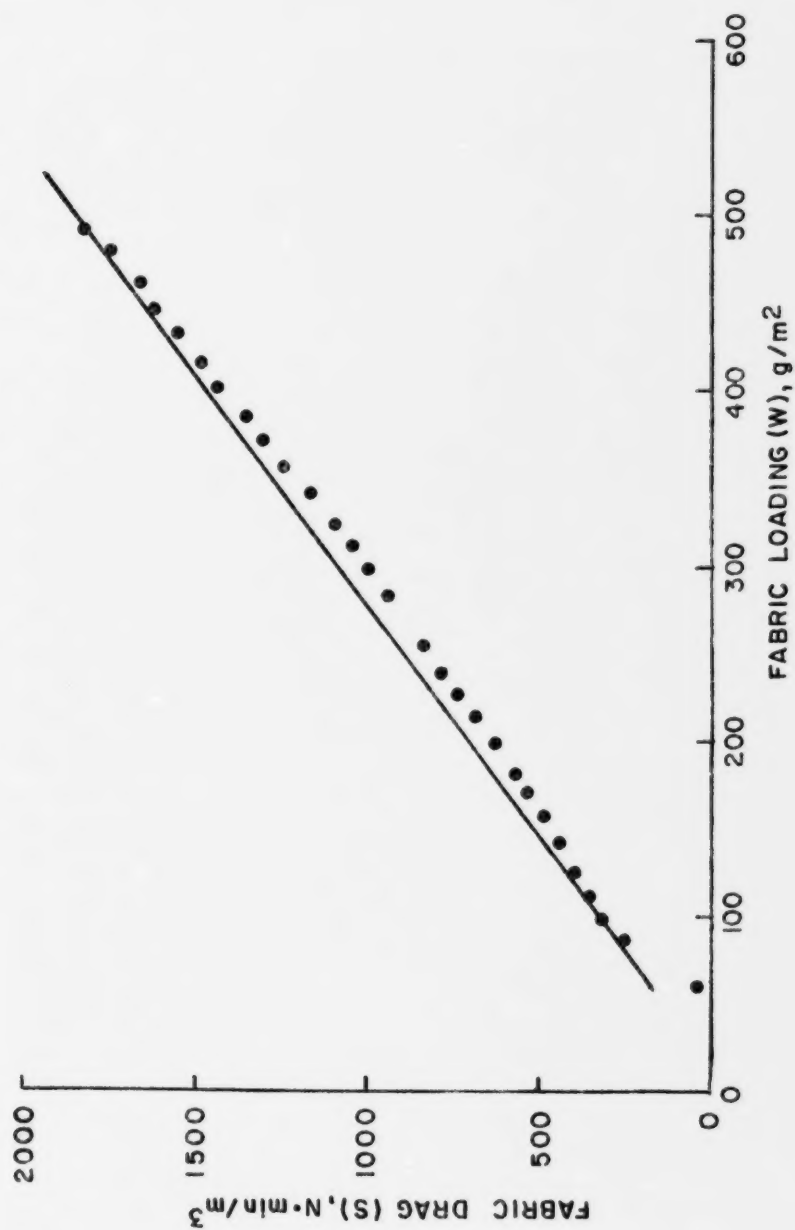


Figure C-3. Drag vs. fabric loading, Kramer Station. $A/C = 0.61$ m/min.

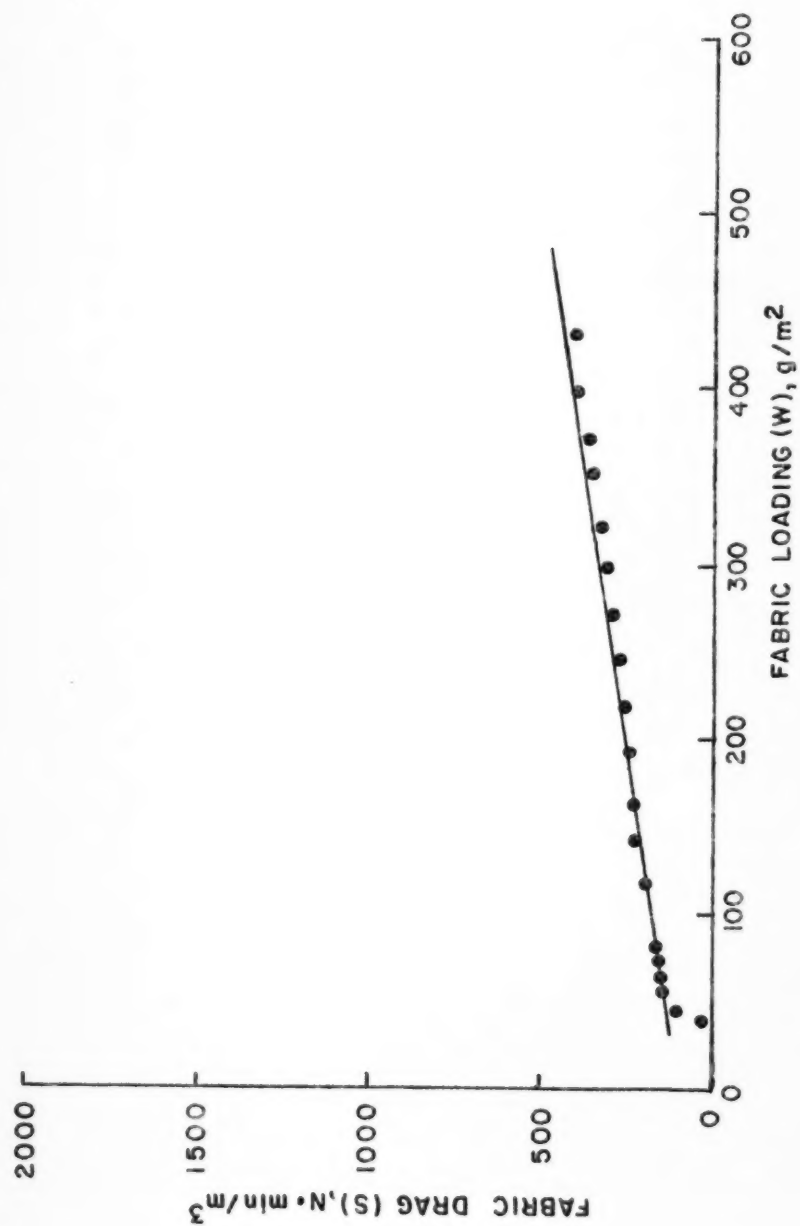


Figure C-4. Drag vs. fabric loading, Texas Utilities. $A/C = 0.61$ m/min.

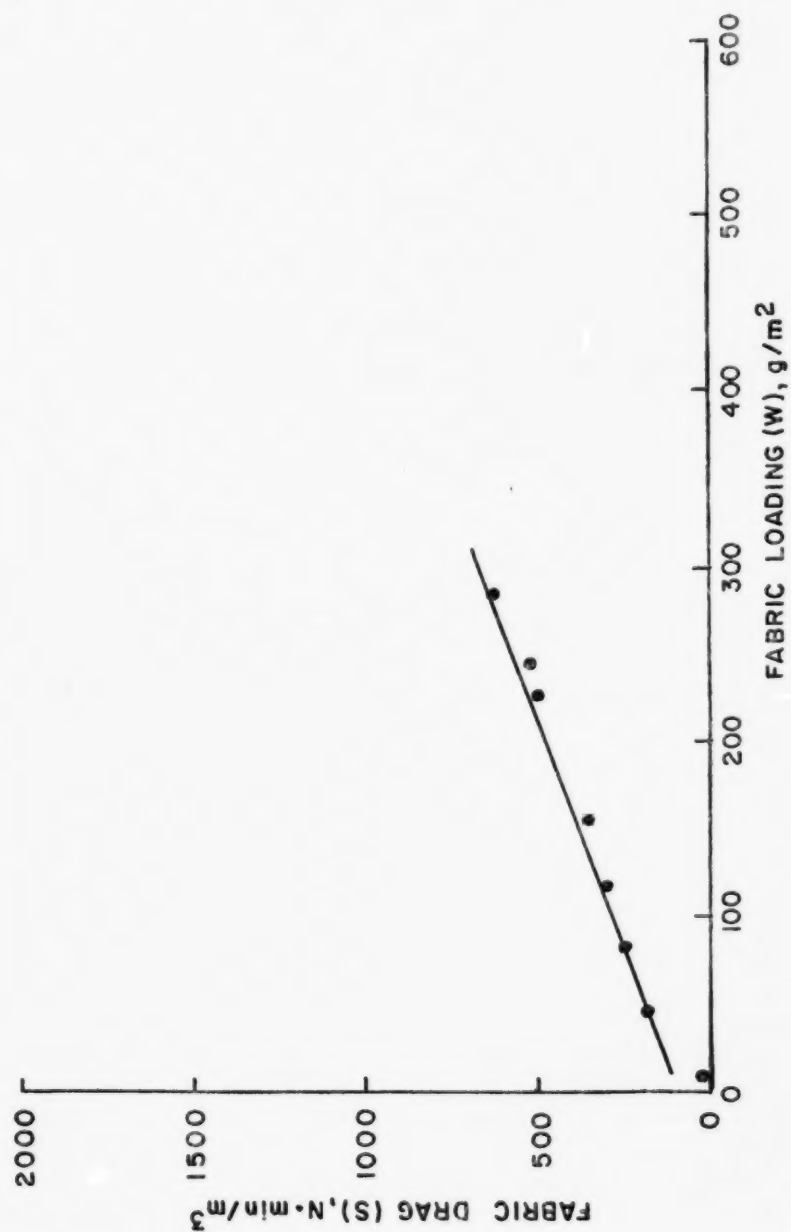


Figure C-5. Drag vs. fabric loading, U.S. Steel. $A/C = 0.61$ m/min.

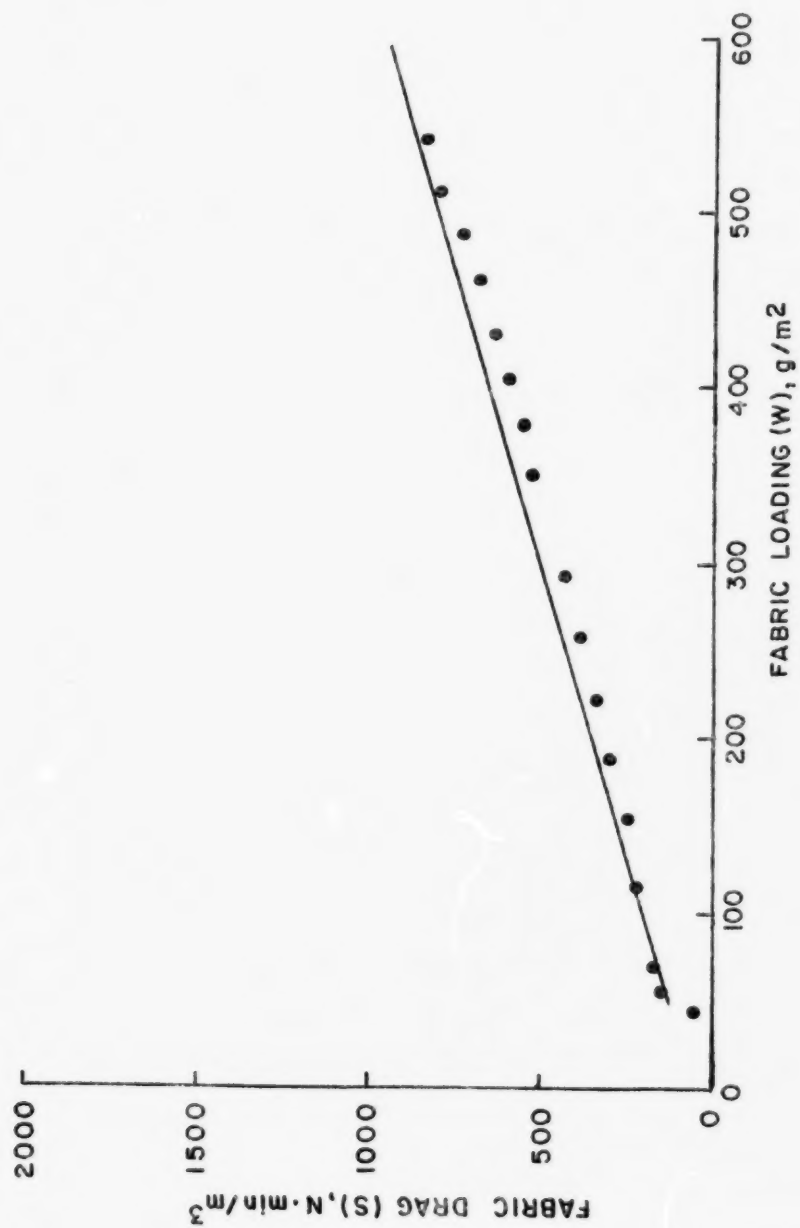


Figure C-6. Drag vs. fabric loading, Amalgamated Sugar "A". $A/C = 0.61$ m/min.

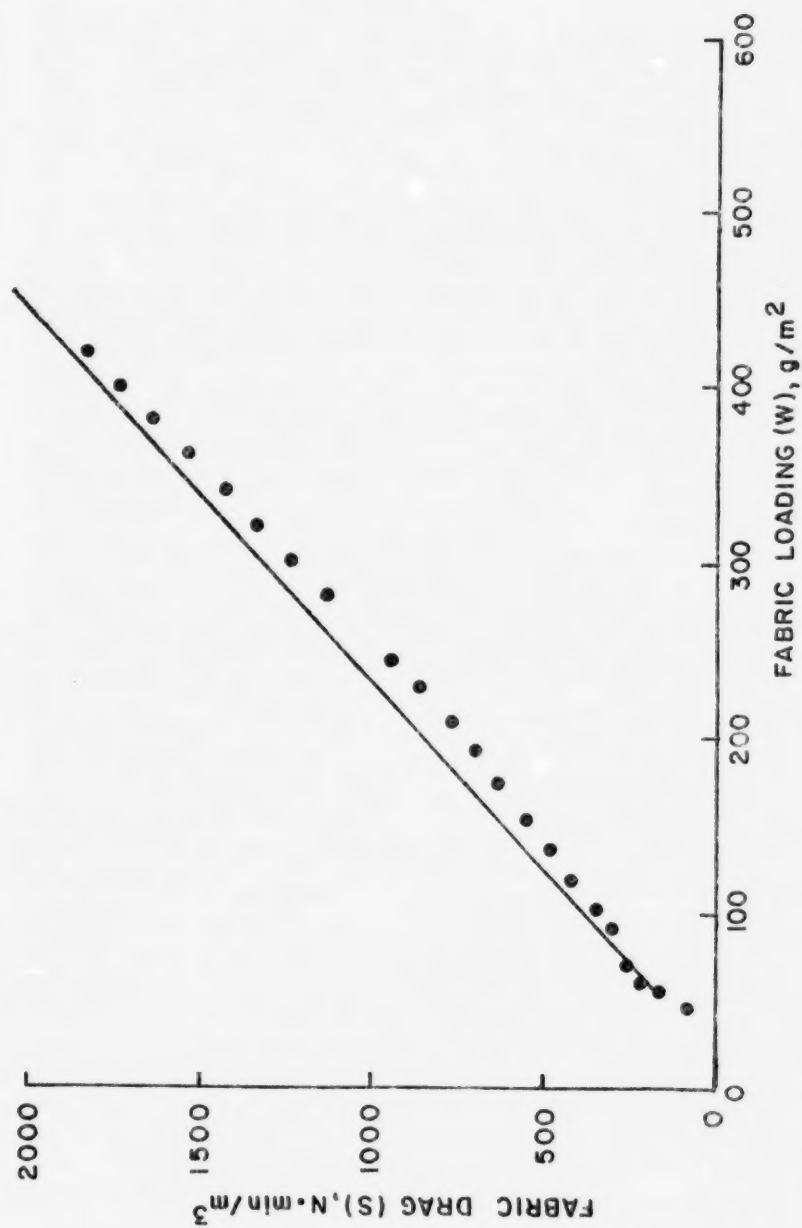


Figure C-7. Drag vs. fabric loading, Amalgamated Sugar "B". A/C = 0.61 m/min.

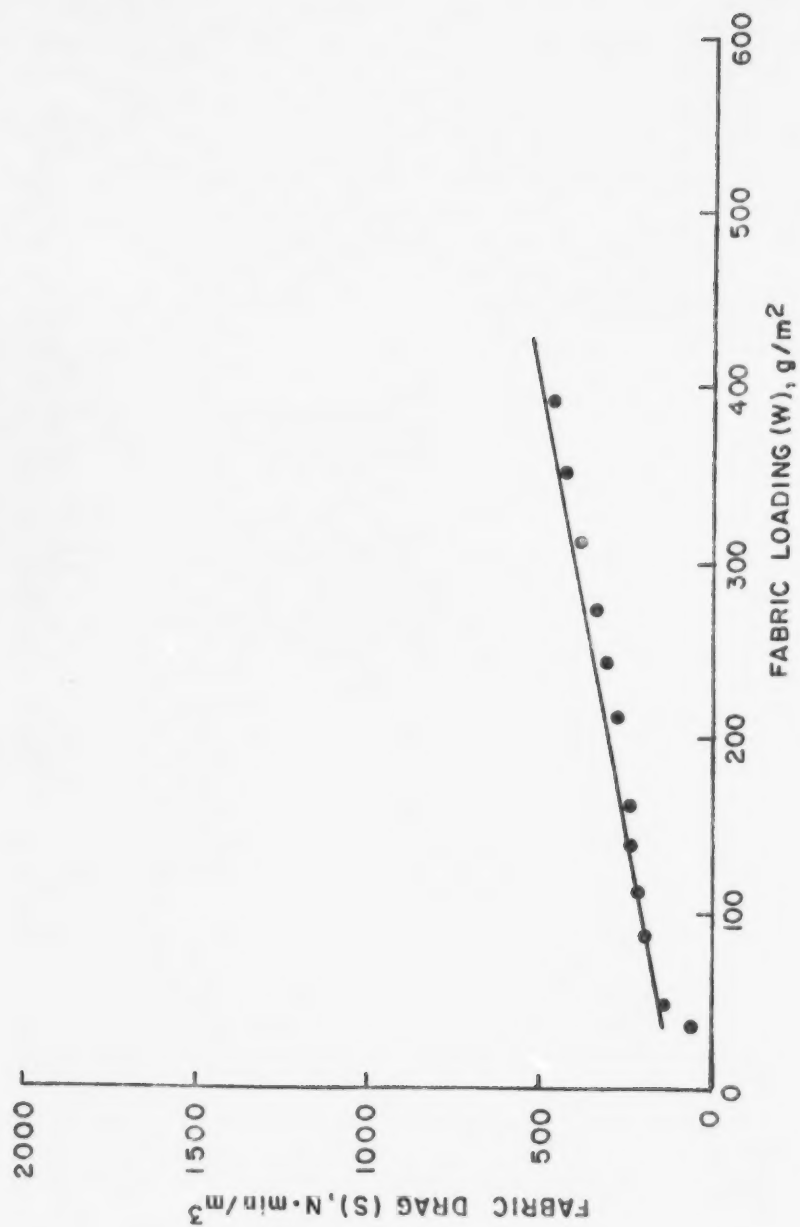


Figure C-8. Drag vs. fabric loading, PPL, Holtwood. $A/C = 0.61$ m/min.

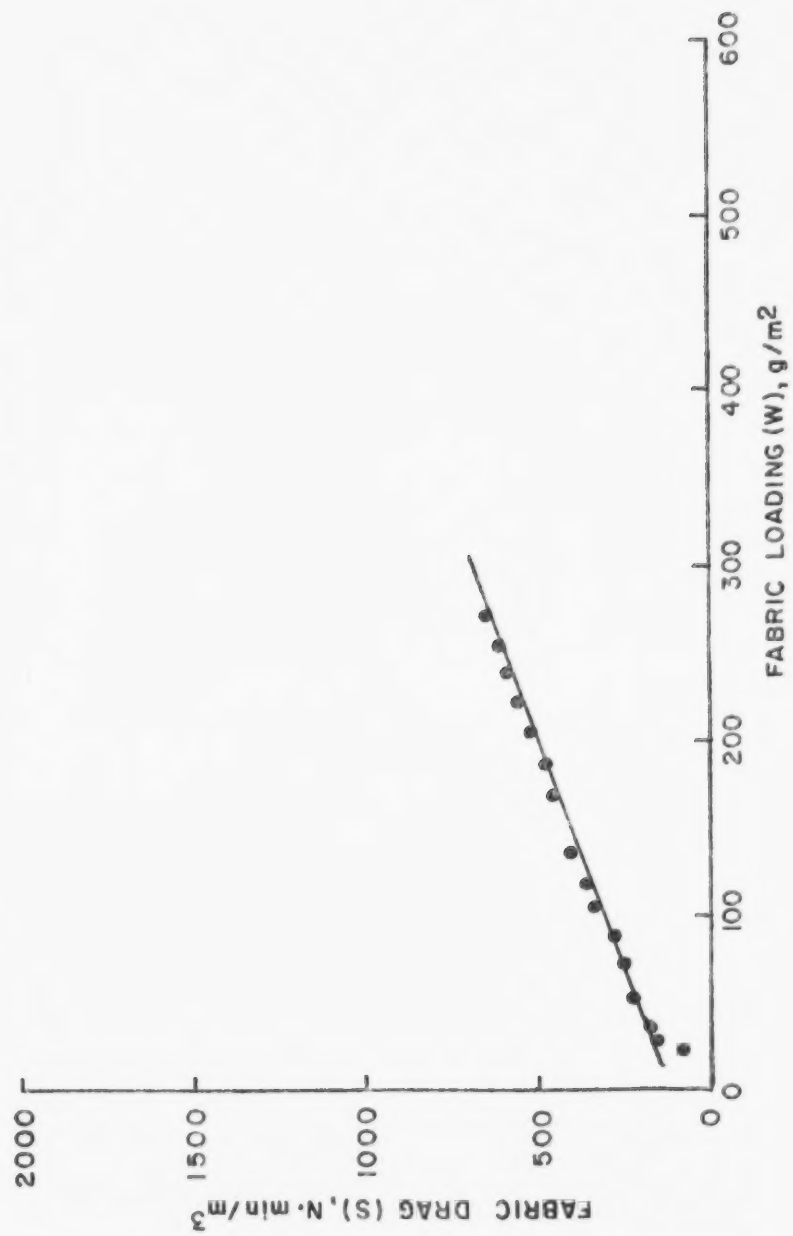


Figure C-9. Drag vs. fabric loading, DuPont, Waynesboro. $A/C = 0.61$ m/min.

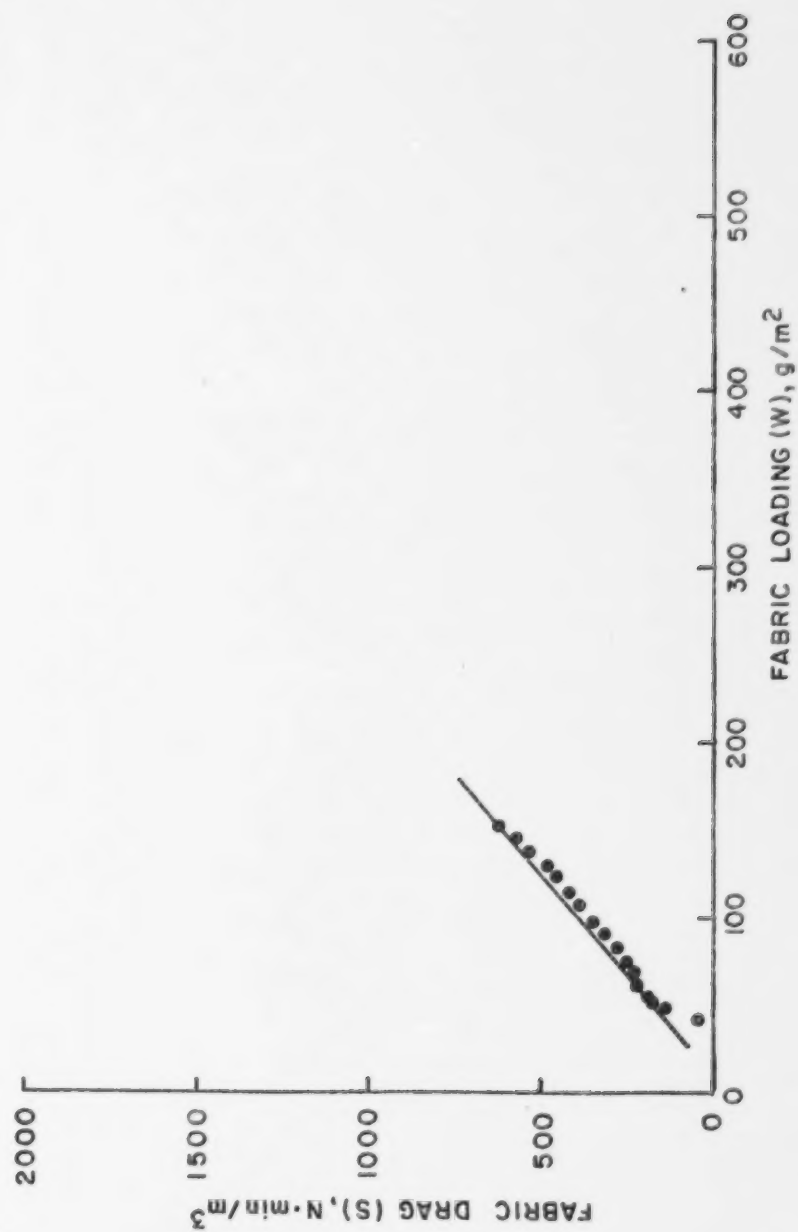


Figure C-10. Drag vs. fabric loading, Westinghouse, Hanford. $A/C = 0.61$ m/min.

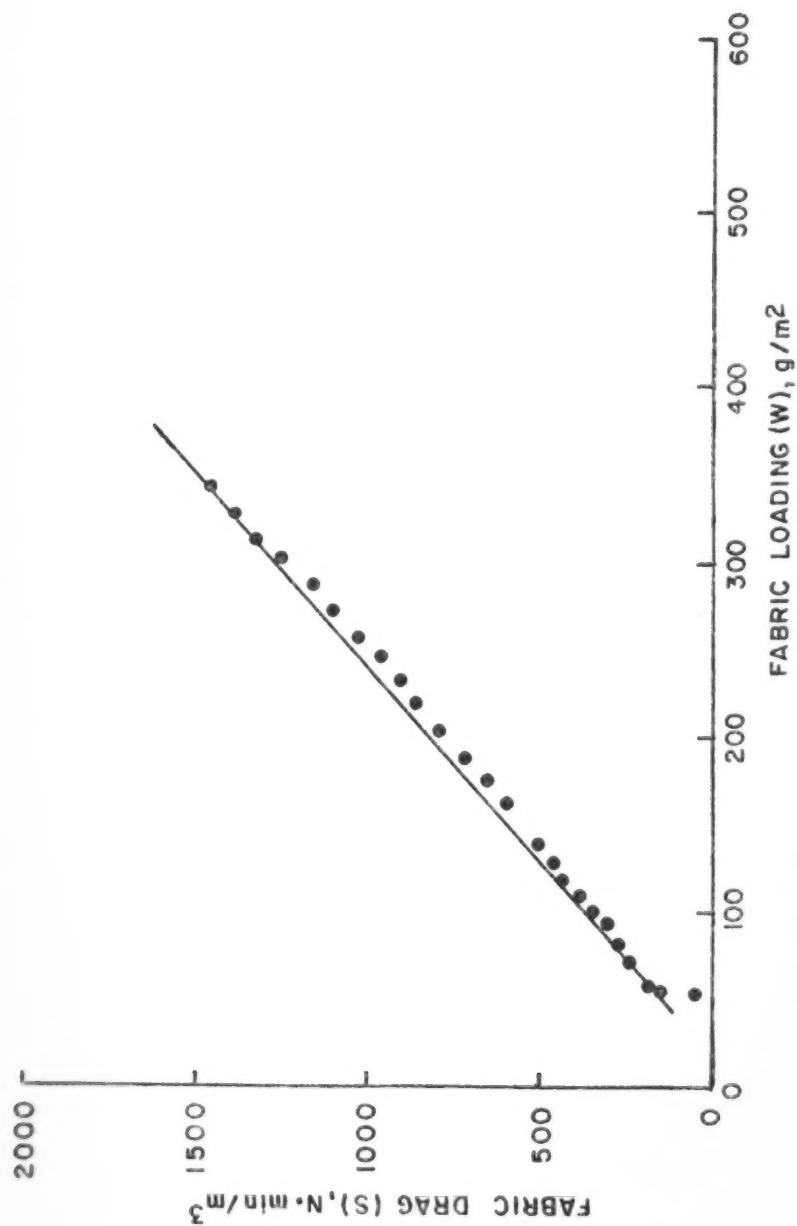


Figure C-11. Drag vs. fabric loading, Case Medical Center. $A/C = 0.61$ m/min.

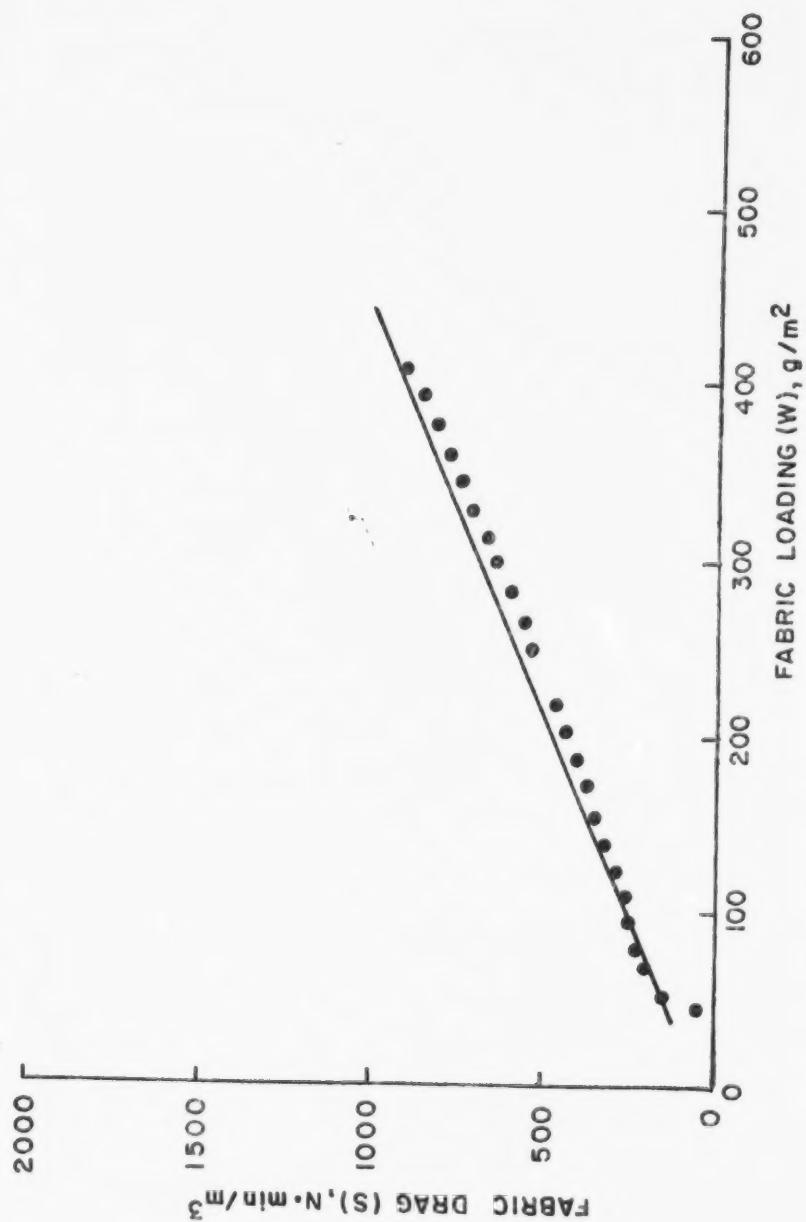


Figure C-12. Drag vs. fabric loading, Republic Steel. $A/C = 0.61$ m/min.

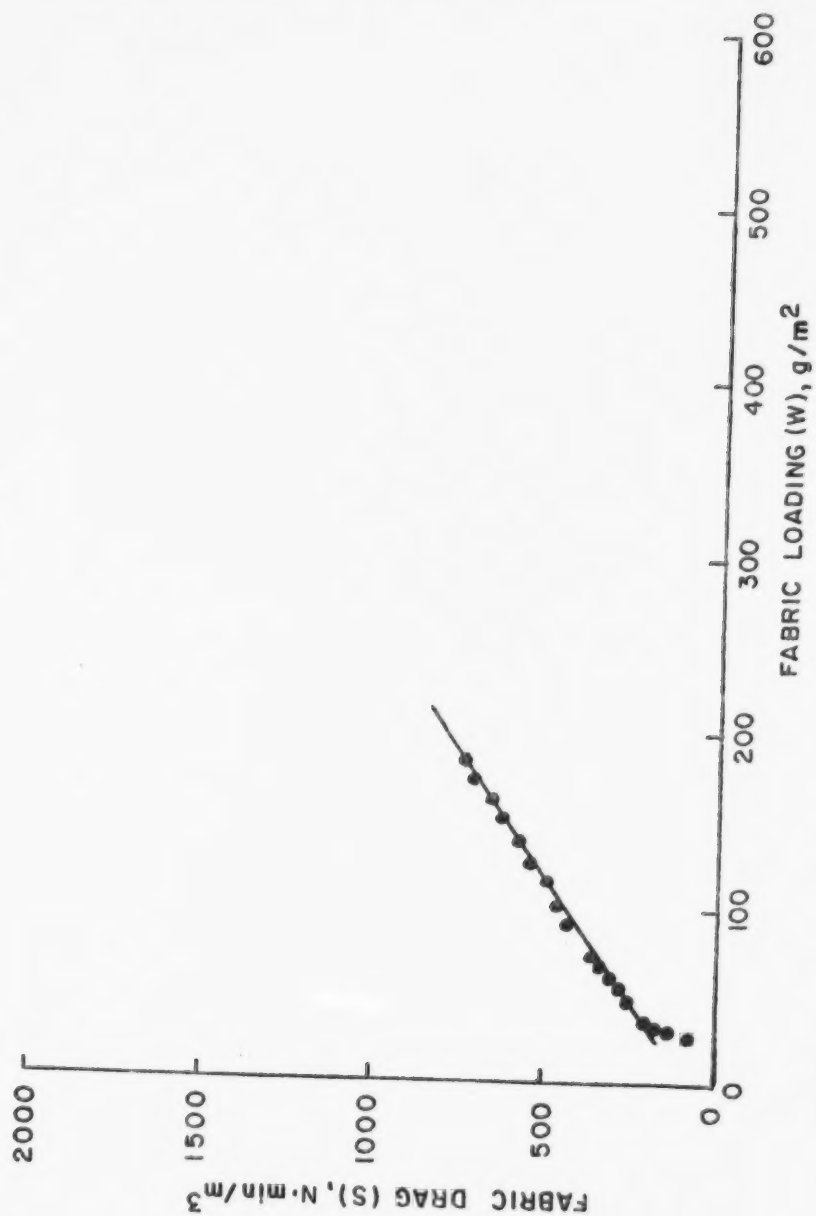


Figure C-13. Drag vs. fabric loading, Colorado Ute, Nucla Station (Hopper Sample). $A/C = 0.61$ m/min.

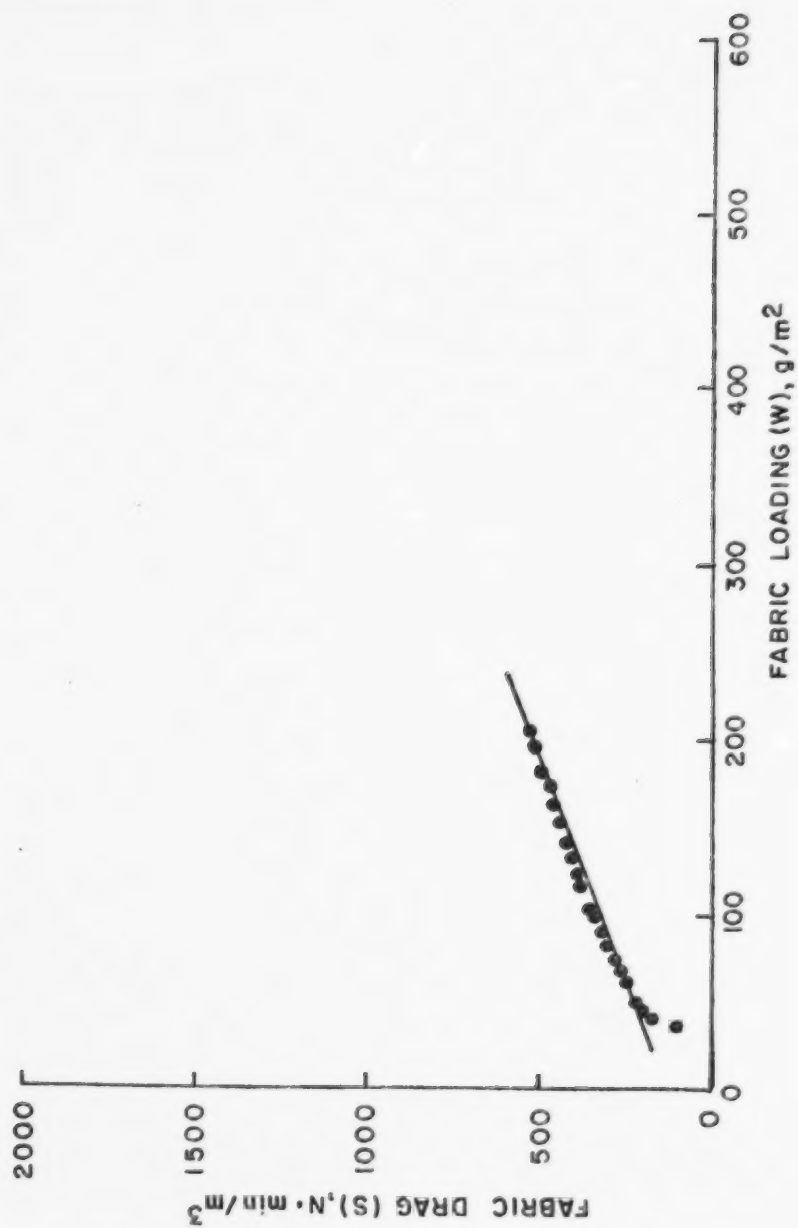


Figure C-14. Drag vs. fabric loading, Colorado Ute, Nucla Station (Bag Shakedown). A/C = 0.61 m/min.